SEA-ICE HABITAT PREFERENCE OF THE PACIFIC WALRUS (ODOBENUS ROSMARUS DIVERGENS) IN THE BERING SEA: A MULTISCALED APPROACH

By

Alexander Edward Sacco

RECOMMENDED: ______________________________

Dr. Hajo Eicken

____

Dr. Mark A. Johnson

____

Dr. G. Carleton Ray

____

Dr. Andrew R. Mahoney

Advisory Committee Chair

____

Dr. Paul J. McCarthy, Chair

Department of Geosciences

APPROVED: ______________________________

Dr. Paul W. Layer

Dean, College of Natural Science and Mathematics

____

Dr. John C. Eichelberger

Dean of the Graduate School

7 December 2015

Date

SEA-ICE HABITAT PREFERENCE OF THE PACIFIC WALRUS (ODOBENUS ROSMARUS DIVERGENS) IN THE BERING SEA: A MULTISCALED APPROACH

A

THESIS

Presented to the Faculty
of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

By

Alexander Edward Sacco, B.S., A.A.S.

Fairbanks, Alaska

December 2015

Abstract

The goal of this thesis is to define specific parameters of mesoscale sea-ice seascapes for which walruses show preference during important periods of their natural history. This research thesis incorporates sea-ice geophysics, marine-mammal ecology, remote sensing, computer vision techniques, and traditional ecological knowledge of indigenous subsistence hunters in order to quantitatively study walrus preference of sea ice during the spring migration in the Bering Sea. Using an approach that applies seascape ecology, or landscape ecology to the marine environment, our goal is to define specific parameters of ice-patch descriptors and mesoscale seascapes in order to evaluate and describe potential walrus preference for such ice and the ecological services it provides during an important period of their life-cycle.

The importance of specific sea-ice properties to walrus occupation motivates an investigation into how walruses use sea ice at multiple spatial scales when previous research suggests that walruses do not show preference for particular floes. Analysis of aerial imagery, using image processing techniques and digital geomorphometric measurements (floe size, shape, and arrangement), demonstrated that while a particular floe may not be preferred, at larger scales a collection of floes, specifically an ice-patch (< 4 km^2), was preferred. This shows that walruses occupy ice patches with distinct ice features such as floe convexity, spatial density, and young ice and open water concentration. Ice patches that are occupied by adult and juvenile walruses show a small number of characteristics that vary from those ice patches that were visually unoccupied. Using synthetic aperture radar imagery, we analyzed co-located walrus observations and statistical texture analysis of radar imagery to quantify seascape preferences of walruses during the spring migration. At a coarse resolution of 100 – 9,000 km^2, seascape analysis shows that, for the years 2006 – 2008, walruses were preferentially occupying fragmented pack ice seascapes range 50 – 89% of the time, when, all throughout the Bering Sea, only range 41 – 46% of seascapes consisted of fragmented pack ice.

Traditional knowledge of a walrus' use of sea ice is investigated through semi-directed interviews conducted with subsistence hunters and elders from Savoonga and Gambell, two

Alaskan Native communities on St. Lawrence Island, Alaska. Informants were provided with a large nautical map of the land and ocean surrounding St. Lawrence Island and 45 printed large-format aerial photographs of walruses on sea ice to stimulate discussion as questions were asked to direct the topics of conversation. Informants discussed change in sea ice conditions over time, walrus behaviors during the fall and spring subsistence hunts, and sea-ice characteristics that walruses typically occupy. These observations are compared with ice-patch preferences analyzed from aerial imagery. Floe size was found to agree with remotely-sensed ice-patch analysis results, while floe shape was not distinguishable to informants during the hunt. Ice-patch arrangement descriptors concentration and density generally agreed with ice-patch analysis results.

Results include possible preference of ice-patch descriptors at the ice-patch scale and fragmented pack ice preference at the seascape scale. Traditional knowledge suggests large ice ridges are preferential sea-ice features at the ice-patch scale, which are rapidly becoming less common during the fall and spring migration of sea ice through the Bering Sea. Future work includes increased sophistication of the synthetic aperture radar classification algorithm, experimentation with various spatial scales to determine the optimal scale for walrus' life-cycle events, and incorporation of further traditional knowledge to investigate and interface cross-cultural sea-ice observations, knowledge and science to determine sea ice importance to marine mammals in a changing Arctic.

Table of Contents

Page

List of Figures

Page

List of Tables

List of Appendices

Page

Acknowledgements

This interdisciplinary work has had guidance and assistance, in many forms, along the way from idea to fruition. First, I would like to acknowledge and thank Andrew Mahoney for allowing me the opportunity to study such an interesting research question in Alaska and providing continual inspiration, support, and guidance. As my primary academic advisor, Andy has provided guidance and assistance throughout my graduate career, and allowed me to explore avenues of research that may not have always been the fastest approach. Andy has also given me many opportunities to broaden my education and career through conferences and meetings; I will continue to be grateful for these experiences in the many years to come. The others on my committee, Hajo Eicken, G. Carleton Ray, and Mark Johnson have each contributed to my academic training in their own way. Hajo has always reminded me to stop and look at the big picture before getting lost in the details. Carleton has taught me that natural history is the name of the game and should always be considered when assessing the ecology of an animal, among many other numerous ideas. Mark showed me the importance of presentation, approaches to analysis, and the basics of Matlab, which have all assisted me on my journey through this study. Overall, I would like to thank my entire committee for providing advice, comments, and suggestions on the thesis work.

A very special thanks to Olivia Lee, research assistant and marine mammal biologist in the Sea Ice Group, for guidance on marine mammal studies, traditional knowledge fieldwork, graduate programs, numerous connections, and reminding me to enjoy myself a bit. Thank you, also, for reviewing my thesis and drafting many recommendations for graduate school pursuits, as well as fostering my interest in marine mammals and encouraging me throughout my graduate career.

The traditional knowledge and satellite study titled “Sea ice conditions and walrus migration near St. Lawrence Island: Integrating local knowledge for assessing change and interpreting satellite data“ was supported by a UAF Center for Global Change (CGC) Student Research Grant (14-012_UAF_GS) with funds from the Cooperative Institute for Alaska Research (CIFAR). I am grateful to a large number of people that were involved in traditional knowledge study in

Savoonga and Gambell on St. Lawrence Island, Alaska. First, I would like to thank Vera Metcalf, who championed my CGC-funded research project on integrating traditional ecological knowledge and satellite remote sensing of walrus habitat. I would also like to thank the entire corporation of Kawerak, Inc., for their continued interest in preserving traditional knowledge and ways of life for Alaskan Natives. I would like to thank the Eskimo Walrus Commission for allowing me to attend and present my research proposal at the 2014 Annual Meeting, including Chairman Charlie Brower, Henry Ivanoff, Elmer Kakaruk Seetot, Jr., Kenneth Kingeekuk, and all of the commissioners from their respective communities that are members in the EWC. I would also like to thank Katya Wassillie for assisting with details for my presentation.

In Savoonga, I would like to thank Myron Kingeekuk and the Native Village of Savoonga for providing me with a place to stay and work during my field visit. Dean Kulowiyi also assisted me during and after my visit with suggestions, insight, and friendship. In Gambell, I would like to thank the staff of the Sivuqaq Inn for providing lodging and work areas and Paul Apangalook and Virgil Soonagrook for assisting me in presenting my research plan to the community and introducing me to hunters. In this study, a number of people participated by providing interviews on walrus and sea ice in the region during the spring migration. To James Walunga and the anonymous participants, I thank you. I would like to thank Laura Eerkes-Medrano for advice, contact lists, and support in this project involving traditional knowledge, as well as specific information on the study areas. In addition to the research side of this project, I would like to thank the numerous administrators who assisted me with this project on the funding side, especially Susan Sugai, and Sarah Garcia.

For the aerial imagery remote sensing data, collected during the 2012 Bering-Okhotsk Seal Survey, a number of NOAA employees provided the data or assisted me in metadata and particulars, including: Kym Yano and Michael Cameron and the entire National Marine Mammal Laboratory in Seattle, Washington. In addition, I would like to thank Kym for inviting me to present my research results at NMML this past summer, 2015.

I must also thank my undergraduate mentor, Audeliz Matias from SUNY: Empire State College, who encouraged me to follow my dreams and educational goals, as well as teaching and instilling in me a love for geology and the earth sciences.

I also thank fellow graduate students that have provided technical, moral, ethical, and research support throughout my graduate career at UAF, including: David McAlpin, Olaniyi Ajadi, Oliver Dammann, Shanshan Li, Megan O'Sadnick, Josh Jones, Heming Liao, Marc Oggier, and others at the Geophysical Institute. I would also like to thank Dr. Franz Meyer for advice on image and geospatial analysis issues. Last, but certainly not least, I would like to thank my father and mother, Ed and Diane, as well as my sister, Kristen, for their endless support and encouragement.

This research is part of the larger project Walrus Habitat and Ice Terrain Mapping Using Video Imaging (WHITeMUVI) conducted by three co-operating universities: University of Alaska Fairbanks, University of Delaware, and University of Virginia. The WHITeMUVI project attempts to identify habitat-scale (1-100 m) sea ice properties that are relevant for walruses by using a deployable 3D terrain camera to be put on icebreakers traversing the Arctic. The ability to map marine mammal habitat in near-real-time from an autonomous ship-based camera has implications for study of ecological data and an opportunity to collect continuous data records from ships sailing the Arctic, both ecological and geophysical.

Over the course of this thesis research, I have received funding from multiple sources, including the National Science Foundation grant #1125040, CDI-Type I: Collaborative Research: A Computational Thinking Approach to Mapping Critical Marine Mammal Habitat Through Readily-Deployable Video Systems. As mentioned above, I gratefully acknowledge the CGC and CIFAR for support in the integration of traditional knowledge and remote sensing of walrus habitat research and would not have been possible without an award from CIFAR. The Alaska Satellite Facility also contributed data and advice on their processing and analysis; I would especially like to thank Scott Arko and Rudi Gens for their generous assistance and patience.

1 Introduction

The Pacific walrus (*Odobenus rosmarus divergens*) uses sea ice for a variety of life-cycle requirements throughout the year, including the spring migration between the Bering and Chukchi Seas (Figure 1.1). The Bering Sea retains ice coverage during the winter and spring. The present study attempts to determine whether patch-scale floe shape and size characteristics, as well as ice-patch arrangements, can be specified to show floe and patch preferences as used by walruses. We also attempt to map walrus seascape habitat similar to previous work (Ray, Overland and Hufford 2010; Ray et al. *forthcoming*). Also, through integration of traditional ecological knowledge (TEK), we hope to gain perspective of walrus use of ice from those that know it best at local scales, namely subsistence hunters of the northern Bering Sea. By these means, we describe walrus dependence on specific ice properties for specific life history activities at multiple scales. Our findings can assist in making decisions about Endangered Species Act (ESA) listing and hopefully will lead to further research about how best to manage the walrus population in light of a changing Arctic climate and sea-ice change. With the receding sea ice extent minimum in the summer and change in ice structure in the Bering Sea, walruses may have to adapt to habitat change for reproductive, calf-rearing, resting, and migration activities in the coming decades. How they will adapt will depend on how ice cover, extent, and structure change in areas that walruses depend on to survive. Therefore, our hypotheses are:

- 1a. The Bering Sea ice pack is composed of regions of ice with distinct properties at the seascape scale;
- 1b. Walruses exhibit a preference for ice with a particular range of properties at the seascape scale allowing potential habitat to be mapped based on the spatial distribution of such properties;
- 2. Within these seascapes, walruses show a preference for specific ice floe properties at the patch scale;
- 3. Use of TEK can supplement scientific study on walrus' use of sea ice.

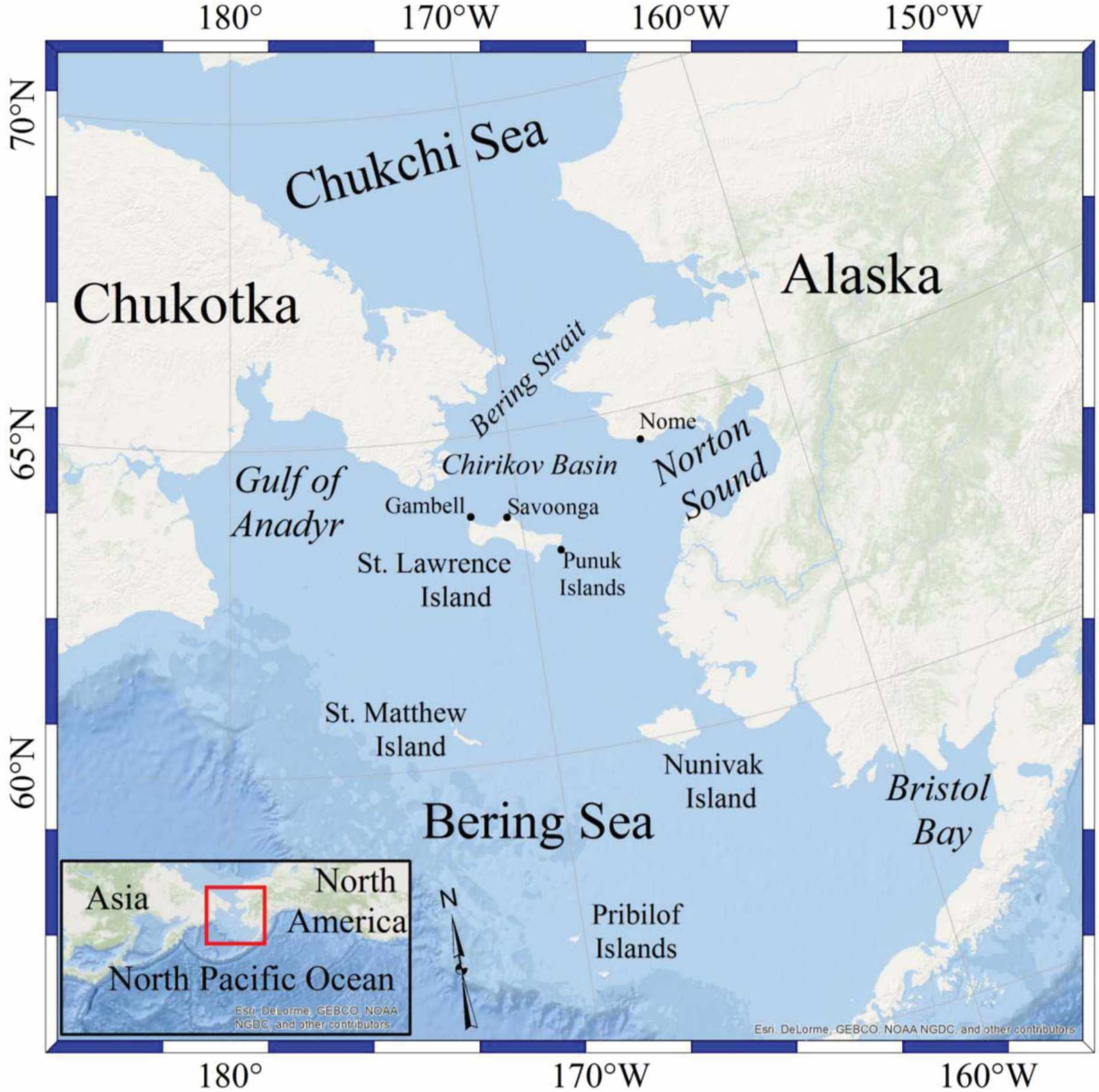

Figure 1.1 Study location map. This map shows the location of the Bering Sea separating Alaska, USA and the Chukotka peninsula, Russian Federation. This map also shows two Alaskan Native villages reliant on walrus subsistence on St. Lawrence Island (Savoonga, Gambell), as well as Nome, AK. This also marks the location of the Punuk Islands, as well as Pribilof, St. Matthew, and Nunivak islands. Lastly, ocean features such as Bristol Bay, the Gulf of Anadyr, the Bering Strait, Chirikov Basin, and the Chukchi Sea are notated.

While the summer Arctic sea-ice extent has decreased to record lows in the past decade (Stroeve et al. 2012), the winter Bering Sea ice extent has remained comparatively steady (Wendler, Chen and Moore 2013). This underscores the need to look at changes in sea ice at multiple spatial scales. As the spatial scale of interest decreases, so too does the relevant temporal scale such that different processes dominate the interactions and properties of the ice (Mcnutt and Overland 2003). For ice-dependent marine mammals such as the Pacific walrus, sea ice processes and properties at a local scale (< 4 km^2), mesoscale (100 – 9,000 km^2), and regional scale (> 9,000 km^2) are particularly important for providing a range of opportunities for walruses that are discussed in more detail below. Similarly, sea-ice processes at these scales may affect hunting success for Arctic coastal communities (George et al. 2004; Kapsch, Eicken, and Robards 2010). Expansion on these three spatial scales of ice dynamics is given in section 1.3.

The Bering Sea is home to five pagophilic ('ice-dependent') pinnipeds: bearded seals, ribbon seals, ringed seals, spotted seals, and walruses. My focus in this thesis is the Pacific walrus, which depends on sea ice for courtship and mating, moving 'central place foraging' platforms (Ray et al. *forthcoming*), resting platforms, transportation for migration, birthing, caring for young (Ray et al. *forthcoming*), and to flee predators including polar bears (*Ursus maritimus*), killer whales (*Orcinus orca*), and humans (Fay 1982). The Pacific walrus is, as of recently, being considered for protection under the ESA of 1973 (Garlich-Miller et al. 2011), mainly due to the predicted loss of habitat caused by a decline in ice availability in summer in the Chukchi Sea. However, sustainability of the species is dependent upon more than predicted habitat loss for the summering females and young walruses. Walrus habitat delineation, especially in the Bering Sea, is needed to assess the risk that this recent decline in sea ice poses to the sustainability of the species' fitness and population continuity. Wildlife management professionals and policy makers are therefore another important group of stakeholders requiring multiscale sea ice data in the Bering Sea.

1.1 Natural history and sea ice requirements of the Pacific walrus

The annual cycle of sea ice advance and retreat dictates almost every aspect of the natural history of Pacific walrus. During the fall, walruses swim south ahead of the advancing pack ice from the Chukchi Sea to the Punuk Islands, southeast of St. Lawrence Island, and other areas surrounding St. Lawrence Island, where they wait for sea ice to become thick enough to serve as a transportation and foraging platform to complete their southern migration to one of three primary wintering grounds: Bristol Bay, the region southwest of St. Lawrence Island, and the Gulf of Anadyr (Fay 1982). In order to forage optimally throughout their winter-spring range, walruses utilize sea ice as a moving platform to feast on bivalves on the ocean floor (Ray et al. 2006). Walruses forage on a 1-3 day cycle with 1-2 days of rest in between (Ray et al. 2006). Once in their wintering grounds, sexually mature males and females engage in courtship rituals in which males attempt to aurally entice the females to choose their mating partner in 'leks' (Fay, Ray and Kibal'chich 1984). Mating arenas consist of areas of open water, either by leads or near polynya features, and thick sea ice on which larger herds of adult and subadult females haul out and males compete for a mate (Fay, Ray and Kibal'chich 1984). Open water surrounding singular floes and leads between larger floes are needed for foraging, diving and auditory displays from males of breeding age. Copulation is suspected to be in-water (Fay, Ray and Kibal'chich 1984). These areas of open water between floes should be large enough for males of breeding-age to compete for female interest and are typically located southwest of St. Lawrence Island as well as near Bristol Bay (Fay, Ray and Kibal'chich 1984).

During the spring, female and young (and some male) walruses begin to travel north on ice floes to the Chukchi Sea through two main routes: (i) along the eastern Bering Sea coastline and (ii) west of St. Lawrence Island. The majority of males swim to coastal haulouts on either side of the Bering Sea. During the spring migration, pregnant females give birth (mainly in the northern Bering Sea), and have been observed remaining on sea ice in areas of semi-isolation away from walrus herds (Fay 1982). Females and their young stay together on ice floes that take them into the Chukchi Sea. Calves are dependent on milk for most of the first year, after which yearlings begin to forage for food on their own. However, young walruses are dependent on mothers for their first two years while males stay two to three years beyond this.

During the spring and fall months of low-ice concentration, walruses are susceptible to predation by polar bears, killer whales, and human subsistence hunters. Active lead systems and pack ice play a role in determining the success of these threats as avoidance is a common response for the walrus (Fay 1982). Thus, particular descriptors for sea ice can be inferred that are essential for walrus natural history. Sea ice requirements are listed in Table 1.1.

Table 1.1 Sea ice requirements of the Pacific walrus based on natural history

Access to open water either through young ice thin enough (< 20 cm) to break through or within the pack ice between floes
Floes large and thick enough to sustain groups of gregarious walruses
Areas of sea ice with leads and/or polynyas to serve as 'leks' during courtship and mating
Floes that diverges so that walruses have access to water under all weather conditions
Semi-continuous seascapes (~ 100 km^2) of similar ice-type that can accommodate walrus herds

1.2 Previous studies of walrus' use of sea ice during the spring melt in the Bering Sea

Walrus habitat delineation has been studied qualitatively, and to a point quantitatively, in the recent past (Burns, Shapiro and Fay 1980; Braham et al. 1984; G. C. Ray and Hufford 1989; Simpkins et al. 2003; Ray et al. 2006; Ray, Overland, and Hufford 2010; Jay et al. 2010; Ray et al. *forthcoming*). However, the ice characteristics previously used have been mainly satellite-derived ice concentration or extent, as described above. The winter-spring months are a critical time in their life cycle when reproduction and migration occur. The sea-ice extent during the spring melt and migration period changes drastically (Ray et al. *forthcoming*, Figure 3). However, the maximum extent that is obtained from regional-scale data does not describe the sea-ice area in depth. Regional-scale sea-ice extent and concentration fail to provide information on small-scale dynamic features such as leads, floe properties and arrangement that may be important to walrus life-history events, and ice-floe motion. Thus, these regional-scale ice data are insufficient in describing the changing ice features that walruses depend on to reach their summer destinations.

In the 1970's and 1980's, numerous walrus population surveys began in which Russian and American scientists collaborated. Burns, Shapiro and Fay (1980) examined multiple marine mammals that interact with the ice cover and could potentially be impacted by exploration activities. Walruses were shown to inhabit three areas of the Bering Sea: south and southwest of St. Lawrence Island, south of Nunivak Island in the southeastern Bering Sea, and in Bristol Bay in areas of drifting pack ice that provides access to open water. Walrus subpopulations are clumped in areas where floes are thick enough to hold their weight and where leads and polynyas are abundant. Braham et al. (1984) examined pinniped ice distribution in the Bering Sea during April, 1976, in a combined Russian-American flight survey over the eastern, western, and southern Bering Sea ice pack. Density of animals and average group size were examined, along with qualitative ice characteristics. While observational descriptions were collected instead of quantitative data of the ice cover, the results are still significant for habitat partitioning. Walruses were observed west and north of St. Lawrence Island and into the Anadyr Strait, which consisted of the highest number of walruses in all areas surveyed. Walruses were also found near Bristol Bay. Dispersal of walruses was more apparent in the southeast shelf than near the Anadyr Strait and St. Lawrence Island region of the shelf. Since walruses were in lower densities near the ice edge in the southeastern shelf than in areas farther away from the ice edge, this suggests that walruses prefer heavier pack ice areas. Walruses were not found in areas of compact ice north of 65° or the Norton Sound area.

Simpkins et al. (2003) utilized digital video frames from an aerial survey conducted near St. Lawrence Island during the March ice extent maximum and concluded that walruses were observed mainly in large-floe (> 48 m) habitat and avoided cake floe (consisting of more than 80% cake floes and brash ice) and low-coverage (0-70%) areas. While the aerial surveys were hindered by storm activity, and short study period, that expanded sea ice southward, possibly causing walruses to disperse from the study area, walrus occupation of these ice characteristics begin to suggest a wide assortment of possible walrus ice preferences.

Jay et al. (2010) used processed SAR imagery to examine whether patch- and seascape-scale (1-100 km) walrus movement was associated with ice movement in the Bering Sea during the spring migration in the northern Bering Sea. Walrus movements were tracked using satellite radio tags and paired with those Radarsat images that were close in collection time. Movement of floe, walrus angle, and displacement were calculated, and a model formulated, to predict walrus-ice displacement and angle difference. The results showed that walrus and ice movement diverged in both angle and displacement for most areas and the study author's conclusions suggested that walruses do not follow a specific floe. During foraging, walruses appear to occupy a particular ice pack type rather than staying with a particular floe. However, whether walruses were able to return to the general sea-ice area, instead of a specific floe, was not investigated, casting doubt on the conclusions.

Jay et al. (2014) studied resource selection by walrus, examining various environmental variables. For sea ice, 6.25-km AMSR-E daily sea ice concentration estimates were utilized for the resource selection model for walruses in the northern Bering Sea. This model showed that ice concentration contributed to the top three performing models for resource selection with an importance of 56% to walrus resource use. While this does support the notion that sea ice is important for walruses as a physical resource, ice concentration, as it is measured, poorly describes ice conditions in terms of ice characteristics that are linked to specific sea-ice utilization by walrus.

In the last 40 years, walrus habitat and ice use studies have become increasingly quantitative and sophisticated. Previous studies have shown that the ice arrangement and evolution is important to daily activities and natural history. Since walruses utilize sea ice in various forms throughout the year, determination of when walrus preferences would play the greatest role in their choice of ice was examined. Sea ice plays a significant role in walrus natural history every month of the year, depending on the sex and age of the animal. Largely, sea ice is heavily used as a means of conveyance for part of the population migrating north in spring. Walruses also need to give birth on ice since young-of-year (YOY) do not have ample insulation, and it is too energetically costly to be in the water for extended periods of time. Utilization of resting and central place foraging platforms is a year-round activity with sea ice as a key support. Thus, the time of year when preferred sea ice habitat for walruses would be most relevant is from January through June. During the winter and spring breakup, various deformation processes operating on different spatial and temporal scales control sea-ice evolution.

1.3 Scaling and describing sea ice

McNutt and Overland (2003) describe a hierarchy of linked spatial and temporal scales for classifying sea ice dynamics. For example, at the floe scale (< 1 km), sea ice dynamics is mainly driven by fracture, shearing, and thermal stresses on a scale of hours to days (Mcnutt and Overland 2003). For time scales of up to two days and spatial scales up to 10 km, floe-floe interactions dominate ice dynamics, as brittle and crushing failure contribute to the changing ice through creation of ridging and rafting features, respectively. The main drivers of ice motion and convergence of floes, ocean and wind forcing, can cause ice to collide and deform, affecting floe thickness and strength. This deformation scale can be considered the “patch”-scale, or ice-patch scale, wherein mechanical and thermal stresses and floe-floe interactions dominate physical sea-ice descriptors that relate to the size and shape of floes over short timescales (1 – 2 days).

Beyond these floe-scale properties, the sea-ice cover begins to behave in such a way that, at the seascape scale, ice deforms as a single plastic continuum for 10 – 75 km over 1 – 3 days. Ice deformation at the aggregate scale can be described such that floe-floe interactions determine internal ice stress, which in turn is scale dependent (Mcnutt and Overland 2003). Here, atmospheric and oceanic effects play a vital role in the fracture and convergence-divergence movement of ice in the seascape. At the coherent scale, from 75 – 300 km over 3 – 7 days, ice deformation, from wind variability in the surrounding area and from boundaries such as coastlines, constrain and allow shear deformation to occur. Thus, seascape spatial and temporal ranges are defined as covering 10 – 300 km and 1 – 7 days, respectively. Lastly, at the climatological scale (300 – 700 km and > 700 km) and from 7 – 30 days and beyond, temporal averaging of sea-ice characteristics tends to smooth ice dynamics in the sub-basin and seasonal sea-ice scale (McNutt and Overland 2003). At the climatological scale, large-scale ice characteristics such as velocity measurements and evolution of the perennial ice cover are observed.

At the patch-scale defined above, the strength of, and interaction between, individual floes is important to pinnipeds. The aggregate scale is used to show that pinniped responses to a changing ice pack of variable-boundary seascapes are dependent on certain seascape properties. Plastic deformation and internal stresses define walrus seascape habitat requirements, which include floe divergence and young ice presence for access to open water and leads for ease of foraging activity and courtship.

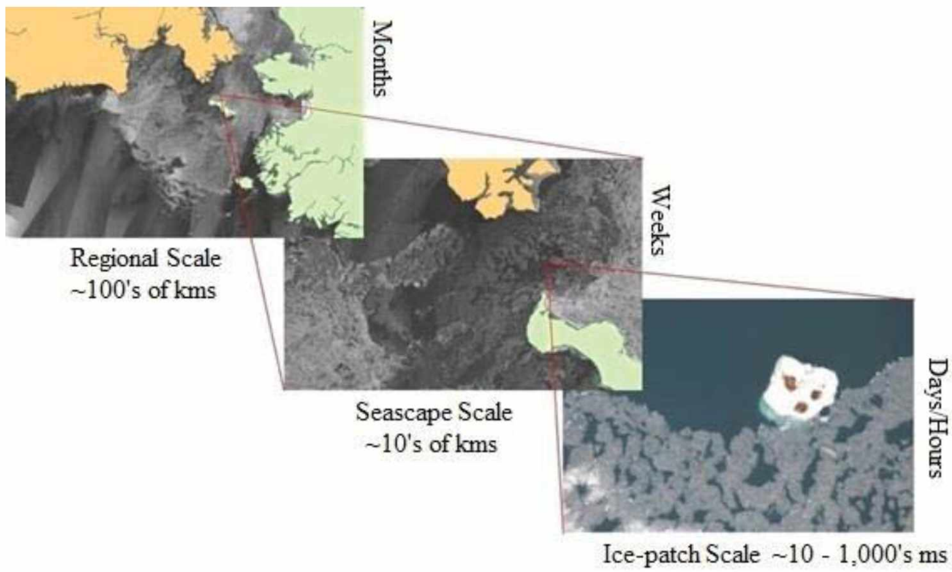

Figure 1.2 Sea ice at the regional, seascape, and ice-patch scales relevant to walrus ice use. The regional scale encompasses months at the spatial scale of 100's of km. The seascape scale covers weeks at a spatial resolution of 10's of kms, while the patch scale covers 10 – 1,000's of m over a period of days to hours. Figure after Ray et al. (2014).

In light of these dynamical ice properties, ice-patch descriptors that may be important for walrus forage-and-rest cycles are typically governed by processes with small spatial (< 4 km^2) and temporal scales (≤ 2 days). This encompasses both internal deformation and floe-floe interactions, which affect the areal ice concentration, the distribution of floe size, shape and thickness. Sea-ice characteristics important to walrus migration and rearing include not only open-water availability, but floe arrangement and velocity at the seascape-scale (100 – 9,000 km^2 in a 1 – 7 day period). Courtship and mating activities are also influenced by seascape-scale ice dynamics, which provide an area for walruses to display in leks. Segregation of the sea ice pack at three spatial scales relevant to walrus ice use is illustrated in Figure 1.2.

1.4 Sea ice descriptors and remote sensing data

Remote sensing data provide measurements of various properties of the ice cover at larger spatial scales and longer temporal periods than field observations allow and in remote areas that can be challenging to access. For example, a number of previous studies (Rothrock and Thorndike 1984; Toyota, Takatsuji and Nakayama 2006; Lu et al. 2008; Perovich and Jones 2014) have used high-resolution aerial or satellite visible imagery to study patch-scale ice properties, including size distributions of ice floes, which may be important to walruses looking for an ice haulout or foraging base.

1.4.1 Ice floe properties

Sea ice floes can be treated as misshapen ellipses in aerial and satellite imagery, providing a mathematical way to describe their shape and size. Floe geometry, including shape, size, and arrangement, is dependent on the scale of observation. These ice characteristics can have varying importance to various sea-ice system users, including the subsistence hunters who encounter sea ice while hunting for food, or an icebreaker captain who needs to consider ice geometry while traversing sea ice-covered waters. Rothrock and Thorndike (1984) examined early spring floe size geometry including (1) area, (2) diameter, (3) mean caliper diameter (MCD), which is a measure of the average diameter of a floe, and (4) perimeter. Rothrock and Thorndike (1984) suggested that floe size distribution could be defined as an amount of fractional area covered by floes above a certain size and the number of floes above a certain size. The number of floes in a given area, or the floe density, was also formulated as a decreasing function of floe area to number of floes per unit area. Using power law distributions of mean caliper diameter and perimeter, Rothrock and Thorndike's (1984) results suggest that certain properties of floes are scale-dependent. Each floe-size distribution that was measured [e.g. area, perimeter, etc.] showed close equivalence to floe-size distributions at other spatial scales. Each floe-size distribution property was inversely proportional to floe density.

Toyota, Takatsuji and Nakayama (2006) examined sea ice floes at three different scales using Landsat, ship-based, and helicopter data. Floe size was defined by the authors as the diameter of a circle that has the same area as the floe, while floe shape was defined as the ratio of the floe size and the diameter based on a circle with the same perimeter as the floe. Toyota, Takatsuji and Nakayama (2006) found that cumulative floe-size distribution varies between the less than 40 m and greater than100 m floe-size diameter scale classes, where floe diameters between 40 m and 100 m acted as a transition between two regimes in the floe-size distribution. Floes below 40 m in diameter exhibit an irregular shape, as is the case with smaller floes that are misshapen from ice thickness variations, melt processes, and floe-floe or floe-wave interactions (Toyota, Takatsuji and Nakayama 2006). At over 100 m diameter, swell can play a major role in mechanical failure, and below 40 m, floes are much less likely to be broken up mechanically. Size distribution of floes, also has a large effect on the lateral melting processes. A comparison of floe size distribution and lateral melting effects were investigated in Perovich and Jones' (2014) study utilizing an aerial imagery time series, finding that, as ice concentration decreases through summer, floe perimeter and density increases. Increases in floe perimeter should allow for more walruses to haul out on a particular floe. A floe density increase would allow for an increased availability of floes that walruses can choose from to haul out on, while an increase in distorted floe shape will hinder floe convergence and preserve access to open water.

1.4.2 Synthetic aperture radar remote sensing of sea ice

Mapping walrus habitat areas the size of the Bering Sea is not feasible with aerial imagery due to the restricted field of view. MODIS imagery, while unable to distinguish features at the local scale, is adequate at the seascape scale. MODIS is inadequate due to obstructions from cloud cover and the inability to collect data outside of daytime. Instead, we can use synthetic aperture radar (SAR), which is sensitive to the surface roughness and dielectric properties that depend upon the patch-scale features of the ice cover. The dielectric properties of the ice depend upon its impurity content and internal structure, including brine volume and, as ice ages, air bubbles near the surface. These internal impurities cause microwaves to scatter inside the sea ice, leading to attenuation and signal loss. Since microwave signal loss is higher with higher brine volume, first-year sea ice typically returns signal back to the satellite through surface scattering. Surface roughness depends on the age and history of the ice including ridging sails (first-year ice) or rafting (young ice). As sea ice ages, brine drains downward through the sea ice and is flushed into the underlying ocean, lowering microwave attenuation for this older and less-saline first-year sea ice.

In general, older, thicker first-year ice (30 – 120+ cm) will have a mid-level backscatter due to a lower surface brine volume and a rougher surface, leading to volumetric scattering. By contrast, younger, thinner ice (0 – 30 cm) will have a much lower backscatter due to a smoother ice surface that can resemble calm open water. The formation of frost flowers, generally caused by a large variation of ice to air temperature, roughens the ice surface. Frost flowers on young ice can therefore produce a stronger backscatter response than older first-year ice. Ridges or rafting on sea ice also enhance the backscatter properties due to an increased roughness, from sea-ice ridge sails producing a stronger backscatter than the surrounding flat sea ice. Open water is a surface scatterer and will appear very dark as long as wind forcing is not present, and is usually easily distinguished from sea ice during the winter and spring months. It is important to note that the backscatter signature of sea ice depends not only upon the properties of the ice, but also the incidence angle, polarization, and wavelength of the microwave signal used. Larger electromagnetic wavelengths can penetrate further into the ice surface. Thus, a lower wavelength, such as microwave C-band (5.6 cm for Radarsat-1) allows less penetration into sea ice than L-band (23 cm for ALOS-PALSAR).

Shokr (1991) used texture analysis and SAR data to study classification techniques for sea ice type. The results showed that various types of sea ice exhibit neighborhood texture variances sufficient to distinguish them in a SAR image, on a pixel-by-pixel scale, based on radar backscatter coefficients. First-year rough, first-year smooth, young, and new ice were studied in order to distinguish these various large-scale ice types using textural statistics and gray-tone measurements using the gray-level co-occurrence matrix technique of Haralick, Shanmugam and Dinstein (1973). While measured gray-tone values were indistinguishable between ice-types, most of the examined texture statistics (uniformity, entropy, inverse difference moment, and maximum probability) were able to distinguish variability among smoother ice types (i.e. new, young, and first-year sea ice) and were unable to reliably distinguish variability in rougher ice surfaces, such as multi-year sea ice. While these ice-types relate to the natural history of walrus ice use, spatial resolution of the data available to describe these ice signatures lies in the seascape scale, where neighborhood comparisons of backscatter are most relevant.

1.4.3 Passive microwave remote sensing data

Passive microwave measurement of sea ice is perhaps the most widely used remote sensing technique used for sea ice analysis due to its temporal range (1979 - present) and global coverage. Passive microwave radiometry data measure the thermal radiance of the Earth's surface. Since clouds do not emit much radiation at the microwave wavelength, emissivity of the surface can be collected without hindrance from clouds. Open water has a significantly lower emissivity than sea ice (Massom 2009). Thus, even though ice typically has a lower surface temperature, its emissivity-dependent brightness temperature will be higher than that of water. The emissivity contrast between ice and water is such that the brightness temperature of the ocean surface is distinguishable in the passive microwave range and is primarily dependent on the relative proportions of ice and open water present. Thus, the brightness temperature, which depends on the surface temperature and the emissivity, would show a higher brightness temperature for sea ice and thus would appear brighter.

Passive microwave data have a 6.25 – 50 km spatial resolution. Thus, features such as leads, small polynyas, and small floes are not easily detectable. Additionally, uncertainties in concentration measurements of the ice cover can occur during winter within about ± 5% accuracy and in the summer, when melt ponds can appear to be open water areas, the uncertainties in measured ice concentration can be up to ± 20% (Massom 2009). Ice detection near the coast is also unreliable, as the large pixel size of these data typically intersects with the land surface. For ice concentration, the processed data is calculated as an estimate of the sea ice occupying that cell. For these reasons, a habitat-scale analysis of sea ice using passive microwave data would be ineffective, as areas that are important to walruses, such as leads or polynyas, areas near land, and some floes that can support them, are smaller than the instrument resolution.

1.5 Relating nomenclature to spatial ecology across scales

Internationally-recognized nomenclature provides a reference for describing the physical characteristics of the ice system. The World Meteorological Organization (WMO) prescribes an extensive set of definitions for describing the ice cover based on its stage of development and morphological characteristics (World Meteorological Organization 2014). The WMO sea ice nomenclature was created as a standardized product for navigational, operational, safety services, and end-users in ice-covered waters, including three volumes consisting of ice terminology, an illustrated glossary, and an international system of sea-ice symbols (see http://www.aari.nw.ru/gdsidb/XML/wmo_259.php). Definitions cover 220 terms with over 13 sections consisting of terminology for fresh-water ice and sea ice, including new (8 types), young (2 types), first-year (4 types), and old (3 types) stages of sea-ice development, regional ice occurrences (including cover, 9 types of ice concentration, 14 size-dependent floe-size definitions, and 25 ice-arrangement definitions), physical and deformation processes, openings in the sea ice pack, surface features, stages of melt, and terms related to shipping and underwater navigation (World Meteorological Organization 2014). WMO ice definitions are not a direct relation to patch and seascape ice areas, but multiple WMO ice definitions are able to reasonably describe those ice features important to marine mammals in seascape- (Table 1.2), patch-, and the regional scale.

It is important to note that none of the geophysical WMO definitions of sea ice mentioned fully describe the characteristics of the ice pack that are relevant to the study of marine mammal sea-ice use at the patch-scale and seascape-scale. In order to use these WMO definitions, it is important to consider specific traits of a species' natural history in order to understand the significance of any particular property of sea ice and the appropriate scale that corresponds to the manner in which the animal interacts with its habitat. For instance, one of the most widely-used geophysical measurements of sea ice is ice concentration. The WMO defines nine categories ranging from compact ice ("Floating ice in which the concentration is 10/10 and no water is visible") to ice-free ("No ice present") (World Meteorological Organization 2014). However, for a walrus, the general presence or absence of open water may be more important than the exact concentration of ice. As noted by Fay (1982), walruses were found in areas of 20 – 80% ice concentration. Thus, these geophysical definitions of sea ice should be used only as an initial-step towards habitat description and delineation, but consideration of natural history in modifying these definitions to suit the study animal are just as, if not more, important in habitat descriptions. WMO ice terminology covers various morphological and structural variations of the sea-ice pack, but only begins to describe the complexity of a changing ice cover that serves as habitat.

1.6 Climate and sea ice in the Bering Sea

The September minimum Arctic sea ice extent (representing the area of perennial sea ice remaining each year) is decreasing by approximately 14% per decade (Overland and Wang 2013). In the Arctic as a whole, sea ice age and thickness distribution have been on the decline for the past 20 years (Serreze and Stroeve 2015). This decline in thick multiyear ice contributed to growth of a younger Arctic ice pack, which is more susceptible to melt each summer, leading the way to an ice cover increasingly composed of seasonal ice.

In the Bering Sea, ice growth is greatest early in the winter during walrus migration and subsequent travel to foraging grounds, where the ice reaches its maximum extent, typically in March. From the maximum ice extent onward, ice begins its decay and melting phase with retreat to the north through June/July, by which time the Bering Sea is typically devoid of ice. After the summer ice extent minimum in September in the Arctic, sea ice begins its growth period, extending south. With it, walruses begin their fall migration south ahead of the oncoming ice pack, in order to ride floes to their destinations in the eastern and western Bering Sea.

Table 1.2 Seascape-scale sea-ice conditions and their relationship to WMO terminology. Seascape-scale (from Ray et al. *forthcoming*, Table 1) WMO-derived ice characteristic definitions as they relate to proposed ecological requirements of marine mammals.

Seascapes from Ray et al. *forthcoming*	Ice important to marine mammals from Ray et al. *forthcoming*	WMO terminology (World Meteorological Organization 2014)
Seascape	An area of sea ice 100 – 9,000 km^2, encompassing one of six sub-regional seascape definitions.	Small Ice Field (4.4.1)
Continuous pack ice	Area of compact, almost continuous ice, with compacting and compressing floes.	Compact Pack Ice (4.2.1) and Consolidated Pack Ice (4.2.1.1) with mainly Vast (4.3.2.2) floes
Rounded ice pack	Sub-type of continuous pack ice. Floe shapes support coalescence of individual floes together, along with convergent trajectories, to create an impenetrable area of ice with minimal to non-existent open water access. Ridging is not uncommon. Ice deformation (rafting) occurs during convergence.	Compact Pack Ice (4.2.1) and Consolidated Pack Ice (4.2.1.1) with Small (4.3.2.5) to Vast (4.3.2.2) floes
Broken pack ice	Floes dispersed and semi-compact to loosely packed. Area between floes provides access to open water.	Close Pack (4.2.3) and Open Pack (4.2.4
Pack ice with leads	Area of small to large congealed floes, consisting of leads perpendicular to wind direction. Leads provide access to open water surrounded by compacted ice.	Compact Pack Ice (4.2.1), Very Close Pack Ice (4.2.2).). Leads (7.3) also present in compacted areas
Loose pack ice	Ice in the fringe area near the marginal ice zone. Can also encompass an ice field of low concentration ice (<1/10 to 3/10).	Very Open pack Ice (4.2.5) and Open Water (4.2.6)
Polynyas	Defined as a non-linear opening between the consolidated ice pack and a landmass. Areas can be latent heat (wind forcing) driven. Latent heat polynyas contain either open water or very open pack with ice stages varying from new to young ice. Ice moves out of the ice field by wind forcing, which then converges to surrounding ice pack.	Polynya (7.4), and specifically Shore Polynya (7.4.1) and Recurring Polynya (7.4.3)

Surface winds coming from the south push ice against St. Lawrence and St. Matthew Islands creating compacted ice, which is too densely packed for marine mammals. Additionally, as noted by Ray, Overland and Hufford (2010), a densely-packed feature of rounded ice-floes forms that acts as a barrier between Bristol Bay and the rest of the shelf, segregates ice and walrus. While not persistent, this dense-pack of rounded ice seascape hinders marine mammal movement, assisting in segregation of sub-populations of Pacific walruses. Sea ice near the edge of the pack is denoted as the marginal ice zone, the region of sea ice affected by ocean wave and swell energy penetrating the discontinuous ice pack (World Meteorological Organization 2014).

Ice in the Bering Sea is affected by similar atmospheric and oceanic forcing to that in the central Arctic, but owing to its lower latitude and direct connectivity with the Pacific Ocean, there are also significant differences. For example, the Pacific Decadal Oscillation (PDO), a regional weather pattern that effects the variability of the Pacific climate much like an El Niño event, influences air temperature advection into the Bering Sea and depends on anomalous sea-surface temperature (SST) and sea-level pressure (SLP) of the north Pacific. Salinity, mixing, and stratification of the Bering Sea shelf-water also can affect ice growth, where a greater salinity in the upper surface water can decrease the freezing temperature of the ocean, and thorough mixing of the shelf from surface to depth can equally distribute brine that is expelled from aging ice (Sullivan et al. 2014). In addition, currents and shelf topography feed and steer warm water from the south, which can affect the amount of heat present in the water column.

Ice extent in the Bering Sea has also been shown to be related to cyclonic activity. Heavy ice years are associated with lower total numbers of storm centers than light ice years, which are shown to increase with decreasing latitude and the track of storms that enter the Bering Sea and cross zonally along the southern portion of the shelf or northward along the Alaskan side of the shelf (Overland and Pease 1982). In light ice years, warm air from the Pacific causes the ice to be pushed northward, moving the ice edge north and closing polynya areas (Overland and Pease 1982).

The Bering Sea is the location of a number of latent heat polynyas, which occur due to wind pushing young ice away from the area faster than growth can occur (Stringer and Groves 1991). In polynyas, heat is transferred upward to the atmosphere to facilitate freezing of the water column (Stringer and Groves 1991). Prevailing northerly winds in the Bering Sea during winter create conditions for polynya formation on the southern sides of islands such as St. Lawrence Island and St. Matthew Island, and in the Gulf of Anadyr in the northwestern portion of the shelf. The southern St. Lawrence Island polynya is dependent on wind forcing with a median areal extent of almost 3,000 km^2 for the winter months (January – April) before completely opening up with ice retreat (Stringer and Groves 1991).

Trends of ice extent in the Bering Sea have remained generally constant when viewed annually from 1979 to 2012 (Wendler, Chen and Moore 2013). However, when examining the ice cover variability month-by-month, the Bering Sea ice cover was shown to vary by 1.4×10^5 km^2 inter-annually, with the largest ranges of ice area variability over the past three decades being observed in March, April, and June (Wendler, Chen and Moore 2013). This may be caused by a shift in the PDO index, leading to colder temperatures in Alaska and decreasing warm air advection into the Bering Sea area over this time (Wendler, Chen and Moore 2013). Similarly, Brown and Arrigo (2012) found great interannual variability of Bering Sea mean open water area and ice-free season length, with a small decreasing trend over time from 1979-2009. The Chirikov Basin north of St Lawrence Island, when examined as an individual region, shows a significant increase of annual open water season by more than eight days per decade (Brown and Arrigo 2012). Wind direction and surface air temperatures (SAT) during this time show high inter-annual variability, but overall no significant trends are apparent in wind direction or SAT (Brown and Arrigo 2012). Winds generally are northeasterly and SAT remains unchanged overall during winter.

1.7 Thesis overview

An investigation into how walruses utilize sea ice during the spring migration, along with integrating important traditional ecological knowledge into a seascape ecology study with remotely sensed data, is the focus of this thesis. Drawn from field observations and using image analysis and geomorphometrics, we attempt to develop a set of preferences that walruses may show when interacting with ice at multiple spatial scales.

Chapter 2 –*Seascape evolution and Pacific walrus preference of sea ice at multiple scales in the Bering Sea during the spring migration* – explores walrus use of sea ice based on ship-board, airborne, and satellite remote sensing data and observations. A new automatic algorithm for distinguishing fragmented pack ice from homogeneous textures in SAR images is introduced and utilized to examine seascapes that walruses tend to occupy during the spring migration. Also, aerial imagery will be utilized with image analysis techniques to detect evidence for walrus preference of sea ice size, shape, and arrangement descriptors in smaller scale and higher resolution studies.

Chapter 3 – *Traditional ecological knowledge of sea ice and walrus ice-patch preference near St. Lawrence Island* – summarizes findings of a project to integrate TEK with a remote sensing-based study of walrus sea-ice use, conducted during the winter/early-spring of 2015. The results of chapter 2 are compared with TEK in order to assess, qualitatively, the ice conditions that walruses tend to occupy during the spring migration period near Savoonga and Gambell, St. Lawrence Island.

Chapter 4 – *Conclusion* – presents overall, overarching conclusions from the previous chapters. Further, recommendations for future research and continuing the study of the quantitative analysis of seascapes for the Pacific walrus, and other pagophilic pinnipeds are presented.

The research presented within this thesis followed Institutional Review Board (IRB) procedures and was approved by the University of Alaska Fairbanks' IRB Office as Protocol #

662539-2. I completed the required coursework in Social and Behavioral Responsible Conduct of Research (Collaborative IRB Training Initiative Course Completion Record # 14137504) and Social Behavioral Research Investigators and Key Personnel (Collaborative IRB Training Initiative Course Completion Record # 14137503).

1.8 References

Braham, Howard W, J.J. Burns, G.A. Fedoseev, and B.D. Krogman. 1984. "Habitat Partitioning by Ice-Associated Pinnipeds: Distribution and Density of Seals and Walruses in the Bering Sea, April 1976." In Soviet-American Cooperative Research on Marine Mammals . Volume 1- Pinnipeds, edited by Francis H. Fay and Gennadii A. Fedoseev, 25–47. National Oceanographic and Atmospheric Administration.

Brown, Zachary W, and Kevin R Arrigo. 2012. "Contrasting Trends in Sea Ice and Primary Production in the Bering Sea and Arctic Ocean." ICES Journal of Marine Science: Journal Du Conseil 69 (7): 1180–93. doi:10.1093/icesjms/fss113.

Burns, John J., Lewis H Shapiro, and Francis H. Fay. 1980. "Ice as Marine Mammal Habitat in the Bering Sea." In The Eastern Bering Sea Shelf: Oceanography and Resources, edited by D.W. Hood and J.A. Calder, 781–97. Fairbanks: University of Alaska Press.

Fay, F.H. 1982. "Ecology and Biology of the Pacific Walrus, Odobenus Rosmarus Divergens Illiger." North American Fauna, 1–279. http://www.fwspubs.org/doi/abs/10.3996/nafa.74.0001.

Fay, Francis H., G. Carleton Ray, and A.A. Kibal'chich. 1984. "Time and Location of Mating and Associated Behavior of the Pacific Walrus, Odobenus Rosmarus Divergens Illiger." Vol. 1.

Garlich-Miller, Joel, James G. MacCracken, Jonathan Snyder, Rosa Meehan, Marilyn Myers, James M. Wilder, Ellen Lance, and Angela Matz. 2011. "Status Review of the Pacific Walrus (Odobenus Rosmarus Divergens)," 155.

George, John C Craig, Henry P Huntington, Karen Brewster, Hajo Eicken, David W Norton, and Richard Glenn. 2004. "Observations on Shorefast Ice Dynamics in Arctic Alaska and the Responses of the Iñupiat Hunting Community." Arctic 57 (4): 363–74.

Haralick, R M, K Shanmugam, and Its'Hak Dinstein. 1973. "Textural Features for Image Classification." Systems, Man and Cybernetics, IEEE Transactions on. doi:10.1109/TSMC.1973.4309314.

Jay, Chadwick V, Jacqueline M Grebmeier, Anthony S Fischbach, Trent L McDonald, Lee W Cooper, and Fawn Hornsby. 2014. "Pacific Walrus (Odobenus Rosmarus Divergens) Resource Selection in the Northern Bering Sea." PLoS ONE 9 (4). Public Library of Science: e93035. http://dx.doi.org/10.1371/journal.pone.0093035.

Jay, Chadwick V., Mark S. Udevitz, Ron Kwok, Anthony S. Fischbach, and David C. Douglas. 2010. "Divergent Movements of Walrus and Sea Ice in the Northern Bering Sea." Marine Ecology Progress Series 407: 293–302. doi:10.3354/meps08575.

Kapsch, Marie-Luise, Hajo Eicken, and Martin Robards. 2010. "Sea Ice Distribution and Ice Use by Indigenous Walrus Hunters on St. Lawrence Island, Alaska." In SIKU: Knowing Our Ice, edited by Igor Krupnik, Claudio Aporta, Shari Gearheard, Gita J. Laidler, and Lene Kielsen Holm, 115–44. Springer Netherlands. doi:10.1007/978-90-481-8587-0_5.

Lu, P, Z J Li, Z H Zhang, and X L Dong. 2008. "Aerial Observations of Floe Size Distribution in the Marginal Ice Zone of Summer Prydz Bay." Journal of Geophysical Research: Oceans 113 (C2): C02011. doi:10.1029/2006JC003965.

Massom, Robert. 2009. "Principle Uses of Remote Sensing in Sea Ice Field Research." In Field Techniques of Sea Ice Research, edited by Hajo Eicken, Rolf Gradinger, M. Salganek, K. Shirasawa, D. Perovich, and M. Lepparanta, 1st ed., 405–66. Fairbanks: University of Alaska Press.

Mcnutt, S. Lyn, and James E. Overland. 2003. "Spatial Hierarchy in Arctic Sea Ice Dynamics." Tellus A 55 (2). Munksgaard International Publishers: 181–91. doi:10.1034/j.1600-0870.2003.00012.x.

Overland, James E, and Carol H Pease. 1982. "Cyclone Climatology of the Bering Sea and Its Relation to Sea Ice Extent." Monthly Weather Review 110 (1). American Meteorological Society: 5–13. doi:10.1175/1520-0493(1982)110<0005:CCOTBS>2.0.CO;2.

Overland, James E., and Muyin Wang. 2013. "When Will the Summer Arctic Be Nearly Sea Ice Free?" Geophysical Research Letters 40 (10): 2097–2101. doi:10.1002/grl.50316.

Perovich, Donald K, and Kathleen F Jones. 2014. "The Seasonal Evolution of Sea Ice Floe Size Distribution." Journal of Geophysical Research: Oceans 119 (12): 8767–77. doi:10.1002/2014JC010136.

Ray, G Carleton, Jerry McCormick-Ray, Peter Berg, and Howard E Epstein. 2006. “Pacific Walrus: Benthic Bioturbator of Beringia.” Journal of Experimental Marine Biology and Ecology 330 (1): 403–19. doi:http://dx.doi.org/10.1016/j.jembe.2005.12.043.

Ray, G Carleton, James E Overland, and Gary L Hufford. 2010. “Seascape as an Organizing Principle for Evaluating Walrus and Seal Sea-Ice Habitat in Beringia.” Geophysical Research Letters 37 (20): n/a – n/a. doi:10.1029/2010GL044452.

Ray, G C, and G L Hufford. 1989. “Relationships among Beringian Marine Mammals and Sea Ice.” Rapports et Procès-Verbaux Des Réunions Conseil International Pour l’Exploration de La Mer 188: 225–42.

Ray, G. Carleton, Gary L. Hufford, T.R. Loughlin, and Igor Krupnik. 2014. “Bering Sea Seals and Walruses: Responses to Environmental Change.” In Marine Conservation: Science, Policy, and Management, 171–99.

Ray, G. Carleton, Gary L. Hufford, James E. Overland, Igor Krupnik, Jerry McCormick-Ray, Karen Frey, and Elizabeth Labunski. Forthcoming. “Decadal Bering Sea Seascape Change : Consequences for Pacific Walruses and Indigenous Hunters.” Ecological Applications. doi:http://dx.doi.org/10.1890/15-0430.1.

Rothrock, D A, and A S Thorndike. 1984. “Measuring the Sea Ice Floe Size Distribution.” Journal of Geophysical Research: Oceans 89 (C4): 6477–86. doi:10.1029/JC089iC04p06477.

Serreze, Mark C, and Julienne Stroeve. 2015. “Arctic Sea Ice Trends, Variability and Implications for Seasonal Ice Forecasting.” Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 373 (2045). http://rsta.royalsocietypublishing.org/content/373/2045/20140159.abstract.

Shokr, Mohammed E. 1991. “Evaluation of Second-Order Texture Parameters for Sea Ice Classification from Radar Images.” Journal of Geophysical Research: Oceans 96 (C6): 10625–40. doi:10.1029/91JC00693.

Simpkins, Michael A., Lisa M. Hiruki-Raring, Gay Sheffield, Jacqueline M. Grebmeier, and John L. Bengtson. 2003. “Habitat Selection by Ice-Associated Pinnipeds near St. Lawrence Island, Alaska in March 2001.” Polar Biology 26 (9). Springer-Verlag: 577–86. doi:10.1007/s00300-003-0527-7.

Stringer, W J, and J E Groves. 1991. "Location and Areal Extent of Polynyas in the Bering and Chukchi Seas." ARCTIC; Vol 44, No 5 (1991): Supplement: 1–171, January. http://arctic.journalhosting.ucalgary.ca/arctic/index.php/arctic/article/view/1583.

Stroeve, Julienne C., Mark C. Serreze, Marika M. Holland, Jennifer E. Kay, James Malanik, and Andrew P. Barrett. 2012. "The Arctic's Rapidly Shrinking Sea Ice Cover: A Research Synthesis." Climatic Change 110 (3-4). Springer Netherlands: 1005–27. doi:10.1007/s10584-011-0101-1.

Sullivan, Margaret E, Nancy B Kachel, Calvin W Mordy, Sigrid A Salo, and Phyllis J Stabeno. 2014. "Sea Ice and Water Column Structure on the Eastern Bering Sea Shelf." Deep Sea Research Part II: Topical Studies in Oceanography 109 (0): 39–56. doi:http://dx.doi.org/10.1016/j.dsr2.2014.05.009.

Toyota, Takenobu, Shinya Takatsuji, and Masashige Nakayama. 2006. "Characteristics of Sea Ice Floe Size Distribution in the Seasonal Ice Zone." Geophysical Research Letters 33 (2): n/a – n/a. doi:10.1029/2005GL024556.

Wendler, G, L Chen, and B Moore. 2013. "Recent Sea Ice Increase and Temperature Decrease in the Bering Sea Area, Alaska." Theoretical and Applied Climatology 117 (3-4). Springer Vienna: 393–98. doi:10.1007/s00704-013-1014-x.

World Meteorological Organization. 2014. "WMO Sea-Ice Nomenclature."

2 Seascape evolution and Pacific walrus preference of sea ice at multiple scales in the Bering Sea during the spring migration[1]

2.1 Abstract

The Pacific walrus, currently being considered for protection in the United States under the Endangered Species Act, spends winter and spring in the Bering Sea in order to mate, forage, and raise young on sea ice. While summer sea ice decline threatens optimal foraging ability for the walrus population in the Chukchi Sea to the north, changes in the Bering Sea spring ice cover may also represent a threat during critical stages of their reproductive cycle. Using remote sensing techniques to analyze seasonal changes in Bering Sea ice conditions at an ice-patch scale (< 4km^2) and the seascape scale (100 – 9,000 km^2), we investigate the relationship between spatial properties of the sea-ice cover and walrus use of sea ice during the spring-melt period. Using high-resolution aerial imagery of sea ice acquired in 2012, we quantify floe and patch-scale characteristics of the ice cover including the size, shape, and arrangement of ice floes in order to determine whether the ice patches that are visibly occupied by walrus groups differ from those that appear unoccupied. At this scale, we find that a comparison between occupied and unoccupied ice patches suggests walruses have a preference for ice patches with relatively large, convexly-shaped floes and fewer floes per unit area. Additionally, walrus-occupied ice patches had lower concentrations of young ice and higher concentrations of open water than those unoccupied ice patches. To examine migration of walrus herds across the ice seascape, we mapped the distribution of seascapes characterized by open water, dense pack ice and fragmented pack ice using synthetic aperture radar data for the years 2006-2008. The proportion and distribution of fragmented pack seascapes varied annually, but quantitative analysis of ship-based sightings show walruses have a preference for fragmented pack over other areas of the Bering Sea ice cover. Fragmented pack ice covered less than half of the total potential ice area (the area of the Bering Sea that may contain sea ice, bounded by National Ice Center chart extent

---

[1] Sacco, A.E., Mahoney, A.R., Ray, G.C., Eicken, H., and Johnson, M.A., Seascape evolution and Pacific walrus preference of sea ice at multiple scales in the Bering Sea during the spring migration, publication forthcoming.

data to the south and 65° N latitude line to the north), on average, in the Bering Sea during the spring-melt season, but accounted for 69% of walrus sightings, on average. We suggest that a more comprehensive analysis of Bering Sea ice at the seascape scale be conducted to distinguish between various fragmented and homogeneous seascape textures. We further suggest that ice-patch analysis be conducted at a larger scale to take into account a more complete picture of ice-patch descriptors at shorter timescales. Integration of these quantitative results of ice preferences should be taken into consideration for management and future ice and walrus research, while including walrus natural history.

2.2 Introduction

The purpose of this paper is to describe walrus use of sea ice during their foraging and rest cycles, mating, and birthing through their migration across the Bering and Chukchi Seas in the Western Arctic. Since the Pacific walrus is currently being considered for federal protection under the U.S. Endangered Species Act (ESA) in 2017, their association with the ice pack at various scales will be important for future management and policy decisions.

Seascape ecology applies landscape ecology concepts and techniques to study the effects of spatial patterns and geometric properties associated with a specific physical environment on organisms and communities at various temporal and spatial scales (Pittman, Kneib and Simenstad 2011; Wedding et al. 2011). The ocean can serve as foraging grounds, means of transportation, haven from predators, rest platforms (in the case of sea ice or bottom-floor dwellers), or expanses of patch-like migration routes. While landscape ecology began its rise as a discipline in the late 1980's, with European and American foci differing in the past several decades (Wu and Hobbs 2007), seascape ecology is a relatively new discipline in the study of ecological processes across the vast oceans of the world. The concept of seascapes brings with it a number of new challenges for both the species of interest and the geophysicists and ecologists who study them: (1) the ocean surface, itself, is constantly moving, along with the ecological processes and species' of concern; (2) seascapes in one area not only vary in spatial extent, but also in the processes that govern seascape structure over short timescales; this allows for measurability of persistence in shape, size, and location of a particular seascape patch; (3) in particular, animal migrants may travel long distances and never leave a particular patch of habitable features; (4) while these patch features may vary during migration, they may still provide conditions desirable to the species which chooses to travel within it, while encompassing timescales in line with the migration itself. These challenges, combined with those typically seen in landscape ecology, such as creation of ecologically-relevant seascape metrics, meaningful relationships between patterns and processes, and scaling issues (Li and Wu 2004), create a challenging but effective new sub-discipline in which to study organism-environment interactions.

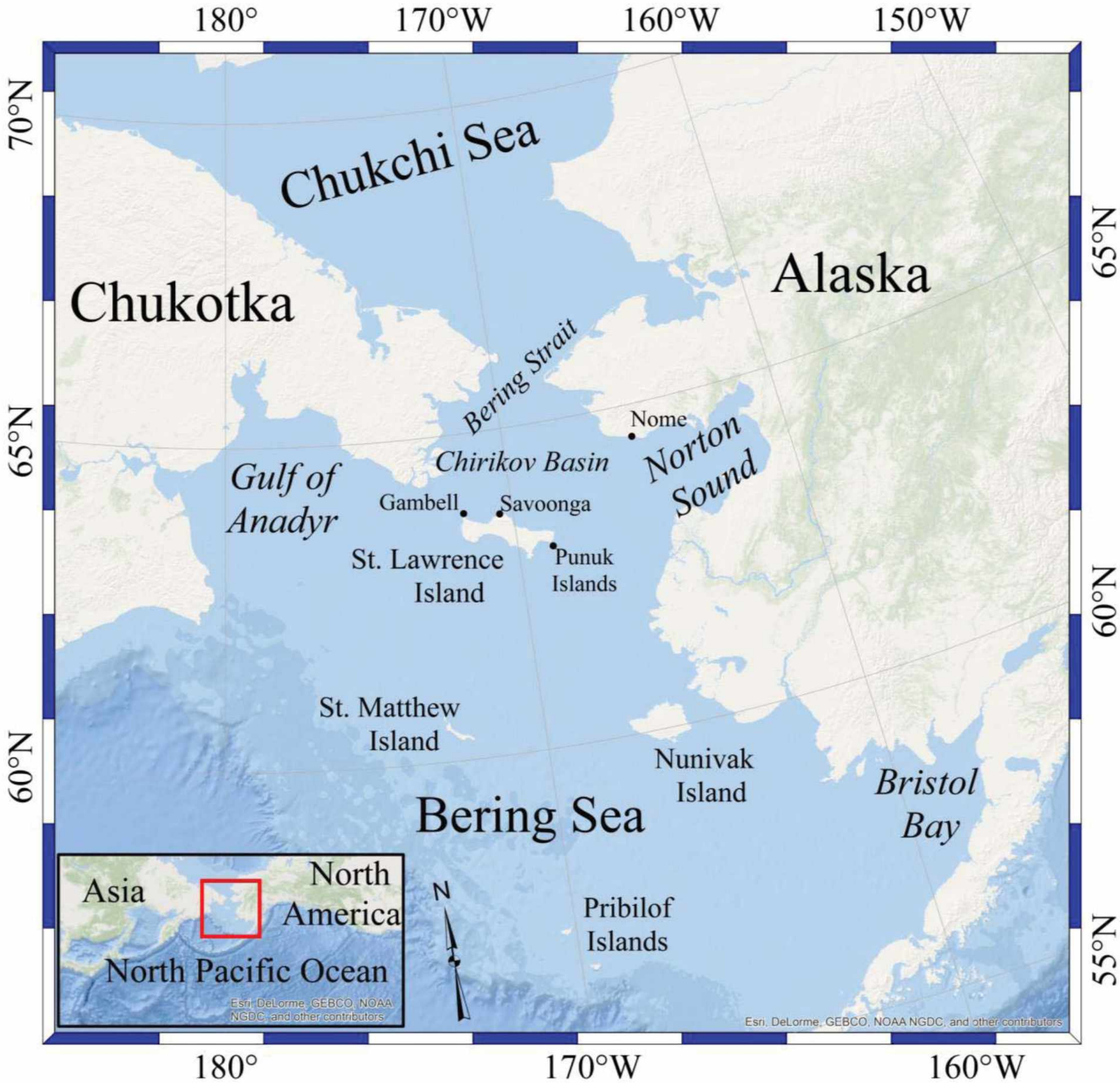

Figure 2.1 Study location map. This map shows the location of the Bering Sea separating Alaska, USA and the Chukotka peninsula, Russian Federation. This map also shows two Alaskan Native villages reliant on walrus subsistence on St. Lawrence Island (Savoonga, Gambell), as well as Nome, AK. This also marks the location of the Punuk Islands, as well as Pribilof, St. Matthew, and Nunivak islands. Lastly, ocean features such as Bristol Bay, the Gulf of Anadyr, the Bering Strait, Chirikov Basin, and the Chukchi Sea are notated.

Satellite measurements of Arctic sea ice have shown a decline in ice extent and concentration during the summer months, with decreasing trends in the past decade (Overland and Wang 2013). Each area that is occupied by sea ice during the year behaves differently, based on geography, bathymetry, oceanic, atmospheric, and climate conditions of the area (Cavalieri and

Parkinson 2012). The Bering Sea (Figure 2.1), which is ice-covered during winter and spring, lies between the East Siberian Peninsula and Alaska. It has been described as a growth-decay conveyor belt of sea ice throughout the ice-occupied months (Pease 1980), constantly replenishing itself through mechanical advection and thermal processes that dominate the sea ice floe life cycle. In this cycle of Bering Sea ice growth and movement, pagophilic (ice-dependent) marine mammals utilize the sea ice for various life history activities including mating and copulation, giving birth, foraging and rest cycles, and migration patterns. In the case of the Pacific walrus' use of seascape in the Bering Sea during the winter and spring seasons, these life history activities and processes may be changing due to a shifting sea ice melt season. This shift stems from changes in seasonal atmospheric forcing in combination with a thinner ice cover and increases in the occurrence of open water within the pack (Brown and Arrigo 2012; Kwok and Cunningham 2015; Wendler, Chen and Moore 2013), resulting in a more rapid and earlier ice retreat (Kapsch, Eicken, and Robards 2010). More importantly, summer ice in the Chukchi Sea which is utilized by female, calves, and some male walruses, has declined in recent years with the summer ice edge retreating far beyond the shelf break, rendering the sea ice unusable for walruses in their effort to forage optimally. This has led female and calf walruses to haul out on Alaskan and Russian coastlines, when these Chukchi Sea-summering walruses would previously stay on the ice throughout the season (Fish and Wildlife Service 2007; Jay and Fischbach 2012).

In order to describe the sea ice characteristics relevant to and potentially preferred by walrus, we investigate the distribution of ice floes across the Bering Sea. Study of the use of sea ice by walruses during the winter months has been limited due to weather conditions and logistical challenges. Studies that have examined the Pacific walrus' association with sea ice at the regional scale (Burns, Shapiro, and Fay 1980; Braham et al. 1984; Jay et al. 2010; Jay and Fischbach 2012) and at the local scale (Simpkins et al. 2003) have focused on sea ice characteristics such as concentration, extent, floe movement, and floe size and type. This, however, can be inadequate for the study of sea ice use by walruses during a critical time in their life cycle when mating, birthing, calf-rearing and seasonal migration occurs. In this study, we examine walrus use of sea ice at two scales: an ice-patch scale (< 4 km^2) and a seascape scale (100 – 9,000 km^2). The ice-patch scale corresponds to ice use on a daily or hourly timescale to describe walrus' feeding and resting cycles, while the seascape scale corresponds to a weekly timescale, which is more applicable to their spring migration activities. These follow McNutt and Overland's (2003) description of sea ice at various spatial and temporal scales, constructed through consideration of the dynamic behavior of sea ice. The combination of McNutt and Overland's "internal" and "multi-floe" scales, wherein internal and floe-floe interactions dominate physical sea-ice descriptors over short timescales (hours - 2 days), encompasses what we define here as the "patch"-scale. At the seascape scale, which overlaps with what McNutt and Overland refer to as the "coherent" and "aggregate" scales, ice dynamics are controlled by continuum mechanics with floe-to-floe interactions essentially treated as internal stresses of the sheet over longer timescales of up to 7 days. A number of sea ice characteristics, or descriptors, are therefore proposed for the ice-patch scale that are potentially important to a walrus in its movement and rest throughout the ice pack of the winter and spring Bering Sea. These descriptors are listed in Table 2.1 . Ice floe roughness may also be important for walrus preference. Roughness features such as ridge sail and keel structures partially determine the response of a floe to wind and current forcing, controlling ice motion. These features may also provide protection from predators or weather extremes. For the seascape scale, we examined mesoscale delineations of the ice pack during the spring melt and migration period in the Bering Sea (*following* Ray, Overland and Hufford 2010; Ray et al. *forthcoming*), which examined segregation of sea ice seascapes that are ecologically relevant to pinniped-use during the spring migration.

The ice-patch scale is investigated using aerial photographs from a survey that spanned the eastern Bering Sea shelf, conducted in spring, 2012 by the National Oceanographic and Atmospheric Administration (NOAA) for their Bering-Okhotsk Seal Survey (BOSS) program (Figure 2.2). To investigate the seascape scale preference of walruses during their spring migration north to the Chukchi Sea, we utilize synthetic aperture radar (SAR) data throughout the Bering Sea in concert with three years of ship- and helicopter-based walrus survey data from 2006 – 2008.

Table 2.1 Patch-scale sea-ice characteristics potentially important for walrus preference

	Definition	Justification
Mean distance between floes	Distance between all floe edges present in a given area	Dependence on availability of open water to escape predators and for ease of foraging
Floe roundness	[1]Ratio of the radii of two circles, one with an area equal to the floe and the other with an equal perimeter	Walruses are observed to have a preference for angular floes
Floe convexity	A measure of indentations, or convex features, of floe shape	Walruses may prefer somewhat convex-shaped floes, as angular floe preference has been observed
Floe area	Amount of space a floe occupies on the ocean surface	Large groups of walruses haul out together and need a large-enough floe
Floe perimeter	Length of a floe's edge	Determines abundance of entry points onto the floe
Floe diameter	Length of greatest distance between floe edges	Need for floes large enough to support groups of walrus
Floe density	The number of floes occupying one unit area	Increases the choice of optimal floes available to an occupant
First-year ice concentration	The fractional area occupied by sea ice thicker than 30 cm, designated as thin, medium, and thick, first-year sea ice (*see* 2.5.1 – 2.5.3 in World Meteorological Organization 2014)	Amount of first-year ice floe coverage available allow walruses to be selective in floe choice
Young-ice concentration	The fractional area occupied by sea ice thinner than 30 cm, designated as nilas to gray-white ice (*see* 2.2 – 2.4 in World Meteorological Organization 2014)	Ability to break through young ice up to 20 cm thick
Open water concentration	An area of the ocean with an absence of sea ice	Ability to escape perceived predators, as well as forage and haul out at ease

[1] $R = \frac{\sqrt{\frac{A}{\pi}}}{\frac{P}{2\pi}} = 2\sqrt{\pi}\frac{\sqrt{A}}{P}$, where A and P are the area and perimeter, respectively, of the ice floe in question; from Lu et al. (2008). The value of R approaches zero as ice floes become elongated in any single direction, or the perimeter becomes increasingly convoluted. The latter effect is scale and resolution dependent since the ability to resolve complex floe shapes will be affected by the size of the pixels in the imagery. Direct comparisons with larger-scale imagery must therefore be made with care.

2.3 Data & methods

2.3.1 Aerial ice and walrus observations

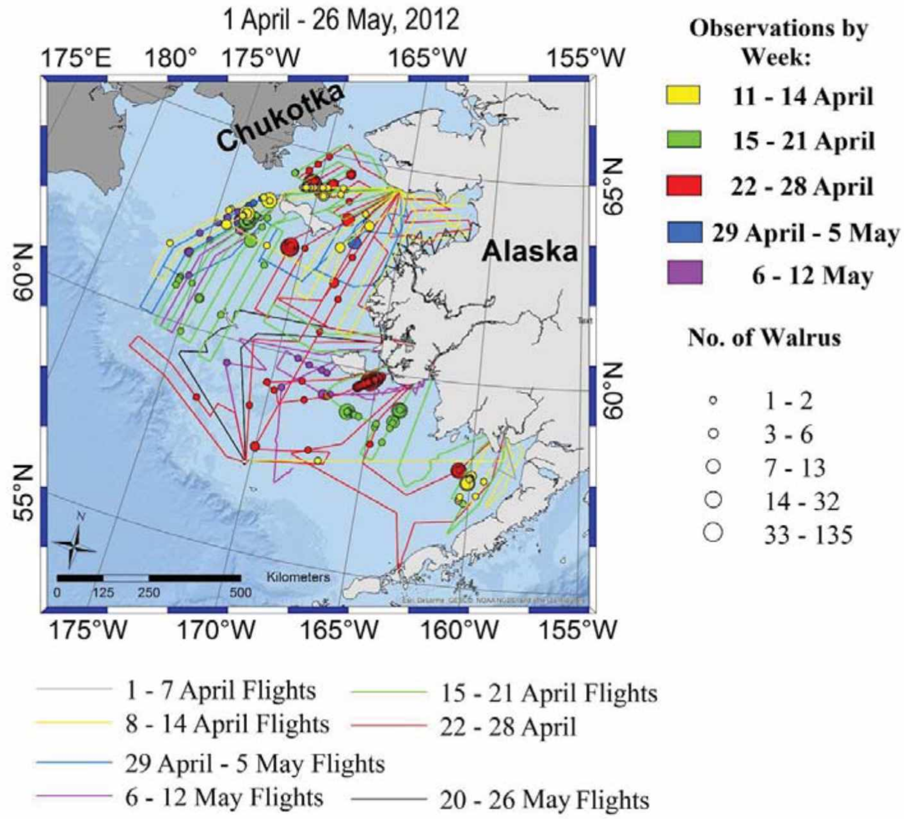

Figure 2.2 Spatial distribution of walruses found in the 2012 NOAA BOSS campaign. Flight lines of 2012 NOAA BOSS are also shown.

To document patch-scale sea-ice associations with walrus presence, we use aerial imagery of sea ice floes and marine mammals in the Bering Sea collected by the National Oceanic and Atmospheric Administration's (NOAA) Bering-Okhotsk Seal Survey (BOSS) program in the spring of 2012, from April 6 to May 23. This program utilized two aircraft (an Aero Commander and Twin Otter, hereafter referred to as the Aero and Otter, respectively) to make daily (and sometimes twice-daily) flights across the Eastern Bering Sea shelf. Between them, the Aero and

Otter covered over 27,000 km with flights lasting four to nine hours (Figure 2.2). Further characteristics of these flights and collected data can be found in Table 2.2.

Table 2.2 2012 NOAA BOSS aerial imagery data description

	Aero flights	Otter flights
No. of flights	18	21
Aircraft	Aero Commander	Twin Otter
Cameras	Thermal: FLIR video infrared camera Optical: 2 Nikon D3X dSLRs (oblique starboard and port)	Thermal: FLIR video infrared camera Optical: 3 Canon 1Ds Mark II dSLRs (vertical center, oblique starboard and port)
Image frequency	~1 image per second taken by each camera	
No. of images collected	489,121	396,613
Extent	52 m x 78 m (mean)	48 m x 73 m (mean)
Total area covered	4,056 m^2	3,504 m^2
Calculated image linear pixel dimensions	Mode: 1.2 cm	
Altitude	Mean: 305 meters (Range: 60 to 3,000 meters)	

Metadata included with imagery provided the latitude, longitude, altitude and attitude of the aircraft as well as the camera focal length for each second of every flight, whether the cameras fired or not. From this information and the timestamp of each photograph, we were able to estimate the geographic coordinates of the camera for each analyzed image. The oblique cameras on the Aero flights were angled at 12.5° pre-flight, while the Otter oblique cameras were angled at 25° pre-flight. At an altitude of 300 m the principle points for the oblique cameras on the Aero and Otter were therefore 67.7 m and 142.2 m, respectively, away from the nadir point. However for simplicity, we did not orthorectify the imagery to account for the oblique angle . This may lead to a bias in the calculation of our floe descriptors, which is discussed in more detail later. In addition, we assumed that the pitch and roll of the aircraft during flight ($\mu_{roll} = 0.89°$, $\sigma_{roll} = 1.12°$ $\mu_{pitch} = 4.18°$ $\sigma_{pitch} = 1.94°$) had a minimal impact on the ground plane geometry of the imagery.

Under these assumptions, each aerial photograph covers a mean effective swath width of 73 m for the Otter flights and 78 m for the Aero flights. The pixel dimension and then, metric image resolution, were calculated using the instantaneous field-of-view (IFOV) and ground-projected instantaneous field-of-view (GIFOV) equations. We obtained the sensor width measurement from the camera manufacturers' websites. The IFOV equation is

$$(1) \qquad \text{IFOV} = 2 * \arctan(\frac{w}{2*f})$$

and the GIFOV equation is

$$(2) \qquad \text{GIFOV} = 2 * H * \tan(\frac{IFOV}{2})$$

where w is the sensor width, f is the lens focal length used, and H is the aircraft altitude. This gives us the ground-plane width of the image. In order to find the pixel size (PS), we use the equation

$$(3) \qquad \text{PS} = \frac{GIFOV}{W}$$

where W is the image width in pixels.

2.3.2 Walrus skin-tone filter

The NOAA BOSS program's main goal was to collect data on four pagophilic seals (bearded, ribbon, ringed, and spotted seals) in order to assess their abundance and distribution throughout the Bering Sea during the spring deterioration of sea ice. Thermal cameras collecting video imaging data were analyzed by NOAA's National Marine Mammal Laboratory (NMML) using thermal imagery-based hotspot analysis to identify seal presence (Burn, Webber and Udevitz 2006). In the course of their efforts, 60 images of walruses were identified through examination of thermal hotspot detection results. These images were used as a training dataset to develop an optical filter technique that identifies objects the same approximate color and size as a walrus. Remote sensing of walruses in optical aerial photography was originally considered in Ray and Wartzok (1974). While thermal-spectrum imagery is typically used for marine mammal detection, some walrus-in-water image results from NOAA's hotspot analysis prompted the use of optical detection techniques that may provide more observations. Since walruses at or right below the ocean surface would be missed by thermal techniques, distinguishing color would provide potential detection of swimming walrus, thus yielding more observations of walruses for this study.

The first step in this approach is to identify image pixels that match the skin tones of walrus. The training images demonstrated that two filters were needed to identify walruses found by thermal imaging. The first filter, or light-skin-tone (LST) filter, is based on single-band and band-difference thresholding for the red, green, and blue channels of the aerial images collected. The equation is defined as:

$$(4) \qquad LST = (R - G) > D_{RG} \cap (R - B) > D_{RB} \cap (G < T_G) \cap (B < T_B)$$

where R, G, and B are the red, green, and blue spectral band digital numbers, respectively. D_{RG} and D_{RB} are the lower-bound threshold values for their respective band differences, while T_G and T_B are the upper-bound threshold values for the green and blue bands, respectively. This binary-image result is then morphologically eroded to remove objects that may match walrus skin-tone, but are too small to be a walrus.

The second filter, or dark-skin-tone (DST) filter, algorithm is also based on single-band and band-difference thresholding, but was created in order to take into account variation of walrus skin-tones due to peripheral vascular constriction, which allows a walrus to reduce heat loss, or peripheral vascular dilation in order to increase heat loss, which can alter the skin-tone of a walrus (Berta, Sumich, and Kovacs 2006). Since these surveys encompass a period when the Bering Sea ice cover is breaking-up and melting, both warm and cold weather should be present and substantially affect walrus skin tones. The DST filter was designed to detect walruses that may have a darker skin tone in the imagery. This DST filter is defined as:

(5) $DST = \{[(R - G) > D_{RG}] \cap [(R - B) > D_{RB}]\} \cup \{[(R - G) > 0] \cap [(R - B) > 0]\} \cap (T_{GBL} < G\ T_{GBU}) \cap (T_{GBL} < B < T_{GBU}) \cap (R < T_R)$

where D_{RG}, D_{RB} are the lower-bound threshold values for their respective band differences, while T_{GBL}, and T_{GBU} are the lower- and upper-bounds for both the blue and green spectral bands. T_R is the upper-bound threshold value for the red spectral band. This binary-image result is also morphologically eroded to remove objects too small to be a walrus. Threshold values for each variable in the LST and the DST are listed in Table 2.3. Threshold values were based on RGB pixel value ranges for existing thermally-detected walrus-occupied aerial images from the same dataset.

Table 2.3 Threshold values for the light- and dark-skin-tone walrus filters

	D_{RG}	D_{RB}	T_{GBL}	T_{GBU}	T_R	T_G	T_B
LST	20	30	–	–	–	200	180
DST	10	5	15	30	75	–	–

Results of the two walrus filters, along with number of images containing walruses found are listed in Table 2.4. The LST filter identified walrus-like objects in 4,126 images, or 0.47% of the complete NOAA BOSS aerial image dataset. Manual inspection of these filter results confirmed the presence of walrus in 194 cases, with the remainder (96%) being found to contain, instead, features of similar color such as sea ice-derived organic matter, excrement, blood, or mature, possibly male, bearded seals, due to the bearded seal's reddish-brown face and neck. By comparison, the DST returned 113,641 images, or approximately 13% of the total dataset. It was not feasible to manually inspect each of these candidate images, so out of all the positive DST filter results, 13,829 images were examined spanning one-half of the camera datasets from the Aero flights and one-half of the camera datasets from the Otter flights, or 12% of the DST results. In the DST results that were examined, 89 were found to contain a walrus, with the remainder, or 99.4% of the visually-inspected images, containing mainly sea ice-derived organic matter. The false-positive rate for the LST was found by calculating the ratio of the number of results from this particular filter that did not contain a walrus to the total number of results of the filter. Similarly, the false-positive rate for the DST was found in the same manner using those results that were visually inspected.

Information gathered from each true-positive walrus observation includes the number of walrus, calf presence, if disturbance is apparent, whether walruses are on-ice or in-water, their geographic location, time of day walruses were observed, and scat presence.

Table 2.4 Walrus filter results for the 2012 aerial imagery dataset

	Flights	Images taken	Filter results (with % of total dataset)[1]	Images containing walrus[2]
Aero flights	18	489,121	36,324 (7.4%)	164
Otter flights	21	396,613	81,443 (20.5%)	120
Totals	39	885,734	117,767 (13.3%)	284

[1]The LST filter resulted in 4,126 results across the entire dataset, accounting for only 0.5% of the total 2012 dataset. The DST filter resulted in the remaining 113,641 results and 12.8% of the total 2012 dataset. Of the results obtained by DST, 12.8%, or 13,829 images, were manually examined.

[2]LST accounted for 194 of the walrus images found, and DST accounted for 89 of the walrus images found. One additional image was found through manual inspection of filter results.

2.3.3 Finding walrus

Results from the two walrus filters identified 284 aerial images of walrus occupation (Figure 2.2). Walruses were found throughout the Bering Sea shelf, with major clusters in Bristol Bay, southeast of Nunivak Island and west of the Kuskokwim River, southwest of Nunivak Island, west of St. Matthew Island, completely surrounding St. Lawrence Island, and into the Chirikov Basin. Some walruses were even near the Pribilof Islands in the far southern area of the shelf. Observations included single and grouped walruses, walruses with calves present, birthing, fleeing into water, creating breathing holes in the young ice, swimming, resting, and possible copulation. Walrus observations spanned five weeks, from 11 April to 12 May in 2012. The largest group size of walruses was 135 individuals, but there were many lone walruses seen. Walruses typically were hauled out on the ice from 12:00 noon to 7:00 pm. Walruses were in water throughout the morning and afternoon into the evening hours. Of all 284 images containing walrus, ~60% were hauled out on ice, while ~40% were in water. Walruses appeared disturbed in over 45% of the walrus-occupied images during the time the photograph was taken. Disruption was defined as any image that showed walruses fleeing into nearby water or looking up at the camera. Out of the total number of walruses observed, considered individually, 97% were adult or juvenile walruses and the other 3% were visibly smaller than the surrounding walruses and were thus considered young-of-year (YOY) walruses. YOY walruses are less than 1 year of age, while juveniles to subadult are aged 1 – 10 years old (Fay 1982). Out of all observations, ~8% of our observations were of adult and/or juvenile walruses with YOY present. While the number of observations of YOY is small, this should only reflect the data set itself, and not the reproductive rate or status of the walrus population.

Table 2.5 Visual observations of 2012 walrus-occupied imagery

	Total no. of walrus	No. of adults	No. of YOY[1]	Images of walruses on ice	Images of walruses in water	No. of images walrus appear disturbed[2]
Visual observations of walruses in aerial imagery	1,075	1,047	28	169	115	134

[1]YOY walruses manually identified by size in comparison to other walruses in the image.

[2]Disturbance determined by either walruses fleeing into water or looking directly up towards the camera

2.3.4 Patch-scale sea-ice analysis from visible band aerial imagery

For each image in which the skin tone filters identify one or more walruses, we select all images acquired 10 s before and after to define the ice patch occupied by the walruses in question. This yields a 20-image area (~70,080 m^2) for Otter flights and 20-image area (~81,120 m^2) for the Aero flights. However, due to unreliable along-track overlap between images, creating an image mosaic was not possible. Thus, each image in the matrix had to be treated separately. Having identified an ice patch occupied by walrus, we noted the number of walruses on the ice and/or in the water, whether the walruses appeared disturbed, whether there were YOY present, as well as any signs of mating, births, or calf-rearing. These sets of walrus-occupied ice patches were then analyzed through image segmentation and geomorphometric measurements. For comparison, we selected a set of non-occupied ice patches by selecting every tenth set of 20 consecutive images from the entire BOSS dataset, excluding images that contained land. These data encompass 4.2% of the total dataset (or 1,859 separate ice patches). This was done to ensure the data would be analyzed in an 'ice-patch'-form, to make the entire analysis computationally feasible, and cover the entire time period of data collected from early-April to late-May. This sample of images was used as an unoccupied-by-walrus dataset in order to compare ice-patch preference that walruses may show. Walruses may be just out of camera range, but within a small distance from the image edge, or walruses may be foraging below the visible range of the ocean surface. While we acknowledge absence of walruses in the image does not mean complete absence from that area, this is a feasible alternative for absence, assuming that we only concerned ourselves with walruses that were visible at the surface. If any walrus-occupied images were present, these ice patches were not included in the unoccupied data set for analysis.

The patch-scale properties of the ice were quantitatively analyzed using a series of digital image processing techniques. First, each optical image was converted to gray-scale from a 3-channel RGB image. This gray-scale image is then segmented into three classes based on the grey-level histogram, following the multi-thresholding extension to Otsu's (1979) thresholding method, which chooses two optimal thresholding locations by maximization of the variance between each of the three classes. The three classes identified approximately correspond to (1) open water, (2) young ice (up to grey-white ice ~ 15-30 cm), and (3) first-year ice (> 30 cm) as defined by the WMO (2014). These thresholds were chosen due to the distinct, easily detected difference in gray value between gray ice and gray-white ice. Assuming that this thickness-based segmentation is correct, it allows us to distinguish between ice nearly thin enough for walruses to penetrate, and ice thick enough to support them. While this is a vast simplification of available sea-ice types (*see* section 1.5 and World Meteorological Organization, 2014), including distinguishing those that are or are not appropriate for walrus occupancy, we chose to minimize the sea-ice type classes to two for simplicity and wider applicability for comparison to other datasets. Having thus segmented the image, we calculate the concentration (area fraction) of first-year ice, young ice and open water.

The regions identified as young ice tend to occupy gaps between the first year ice floes and thus have highly irregular shapes or consist of many conjoined small floes (Figure 2.3). For the purposes of calculating the size and shape descriptors of ice floes, we therefore only consider those regions classified as first year ice. In some cases, the segmentation may forge connections between closely-packed, but separate floes, so we apply morphological opening and closing operators to enhance the separation between floes.

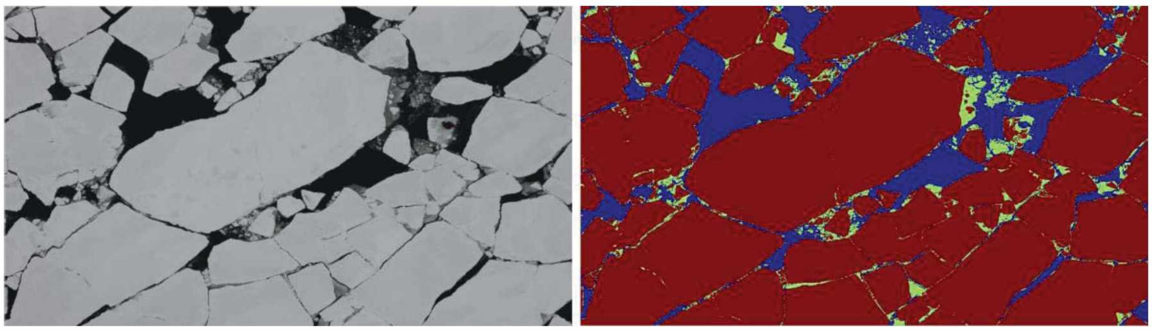

Figure 2.3 An example of floe and water segmentation. This pair of images shows an example of the segmentation algorithm, which separates individual first-year floes from areas of open water and young sea ice. On the right, red denotes thick first-year ice that would be able to support a walrus' weight, while green denotes young ice that walruses are unable to haul out on, but are able to break through in order to create breathing holes, if needed. Blue shows areas of open water, which can be used as an opening for foraging activities or to escape predators.

Objects in the images were separately identified and labeled using Matlab and Image Processing Toolbox's (2012) bwconncomp algorithm. These objects were considered connected if they showed connectivity in an 8-pixel neighborhood. Floes that touch the edge of the image area are excluded from further analysis since the shape and area outside of the image frame is not known. For each completely-captured floe, five separate size and shape descriptors were calculated with assistance by Matlab and Image Processing Toolbox's (2012) regionprops algorithm: (1) area, (2) perimeter, (3) diameter, and (4) convexity. An additional descriptor, (5) roundness, was adapted from Lu et al. (2008), which is defined in Table 2.1 . Since we are concerned with ice patches that walruses can occupy, or show preference for, all floes in an ice-patch smaller than 9 m^2 were excluded since the mean adult walrus is approximately 3 m in length (Fay 1982). Together with the floe density (the number of floes per unit area) and the concentrations of first year ice, young ice and open water, which we will refer to as ice-patch arrangement descriptors, the mean values of these five size and shape descriptors gives us nine ice-patch descriptors with which to quantify the walrus-occupied ice patches.

Ice patch floe size descriptors, such as area, perimeter, and diameter, are properties of floes that determine how many walruses are able to utilize a floe. Since walruses are highly gregarious (Fay 1982), having floes that are both spacious and thick enough is important and therefore these descriptors relate to the number of walruses that can haul out onto a particular floe. Ice patch floe shape descriptors roundness and convexity characterize elongation, angularity, and may relate to the usable area of floes from the perspective of a walrus. Finally, ice patch floe arrangement descriptors of the concentrations of open water, thin ice and first year ice, as well as floe density per unit area, describe availability of floes to choose from, the types of floes to choose from, and the amount of access to open water or young ice that is thin enough to break. Table 2.1 outlines these descriptors in more detail.

Ice-patch floe area, and the rest of the floe-size descriptors, should be considered as an incomplete picture of the size distribution in the Bering Sea at all scales. The scale of consideration here, a 100 m^2 – 4 km^2 spatial area, encompasses multiple, discontinuous aerial images that average these floe descriptors across the entire ice-patch area. Thus, floes cannot exceed a size that is larger than the image ground-size itself. The most probable floe diameter for both the Aero and Otter aerial data does not exceed 24 m and 26 m, respectively (Figure 2.4). This means that larger floes, and at times floes that walruses were hauled out on, touched the edge of the image and were excluded from further analyses. Walruses were on floes that were excluded in 30% of the occupied images. Walrus, especially during the winter months, occupy large floes and areas of leads that would not be encompassed in one aerial image. Since walruses are not expected to be tied to one particular floe, the loss of a small fraction of floes that had hauled out walruses occupying them is not considered as relevant as consideration of the ice patch as a whole. Typical mean floe area of those floes that encompassed some area beyond the visible ground plane was 313 m^2. Ice patch floe shape descriptors were biased due to aerial camera angles that caused shapes to be misrepresented, as well as floe size and area of ice types, which affected our concentration statistics.

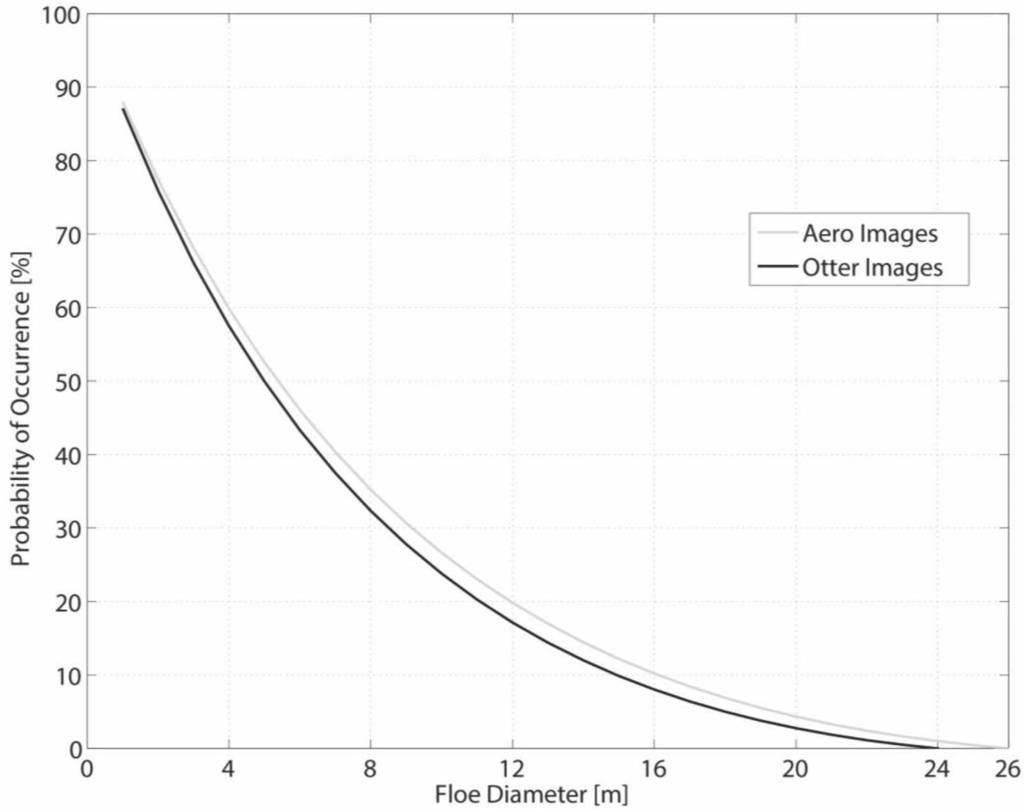

Figure 2.4 Probability of occurrence of floe diameters in Aero and Otter images. Probability is based on image ground size, of floes that are probabilistically likely to be found completely contained within the aerial photos. Note that at 35% probability we reach the mean floe diameters of all our ice-patch walrus occupied and unoccupied classes.

2.3.5 Ship-based walrus observations in the Bering Sea, 2006 – 2008

Four years of walrus observations were collected during USCGC Healy icebreaker cruises in 2006 (HLY-0601), 2007 (HLY-0701/02), 2008 (HLY-0801/02), and 2009 (HLY-0901/02). Data include sightings made by observers on-board, supplemented by observations from ship-deployed helicopter flights (Ray et al. *forthcoming*). From these four cruises, walrus observations were available, for the periods 8 – 29 May 2006, 14 April – 10 June 2007, 15 March – 3 May 2008, and 10 March – 11 May 2009, each resulting in a total number of 5,310, 1,550, 1,805, and 5,370 observed walruses, respectively (Ray et al. *forthcoming*). Each walrus sighting included location and time, the number of walruses sighted and whether they were on an ice floe or in

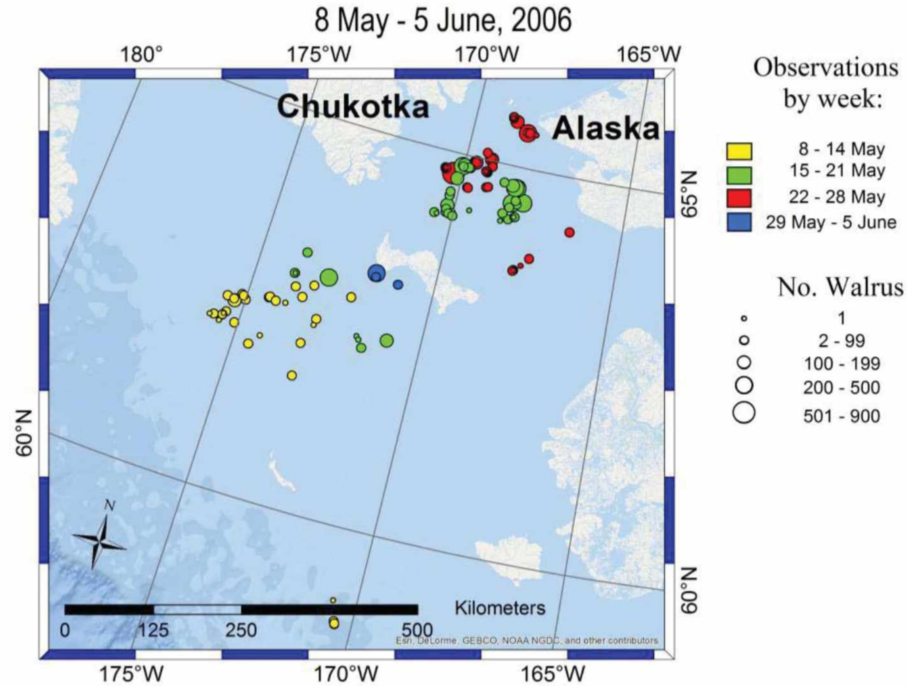

Figure 2.5 Ship-based walrus observations for 2006. Observations collected onboard the USCGC Healy in the Bering Sea during spring. Data were obtained from USCGC Healy cruises 06-01 and Ray et al. (*forthcoming*), http://dx.doi.org/10.1890/15-0430.1.

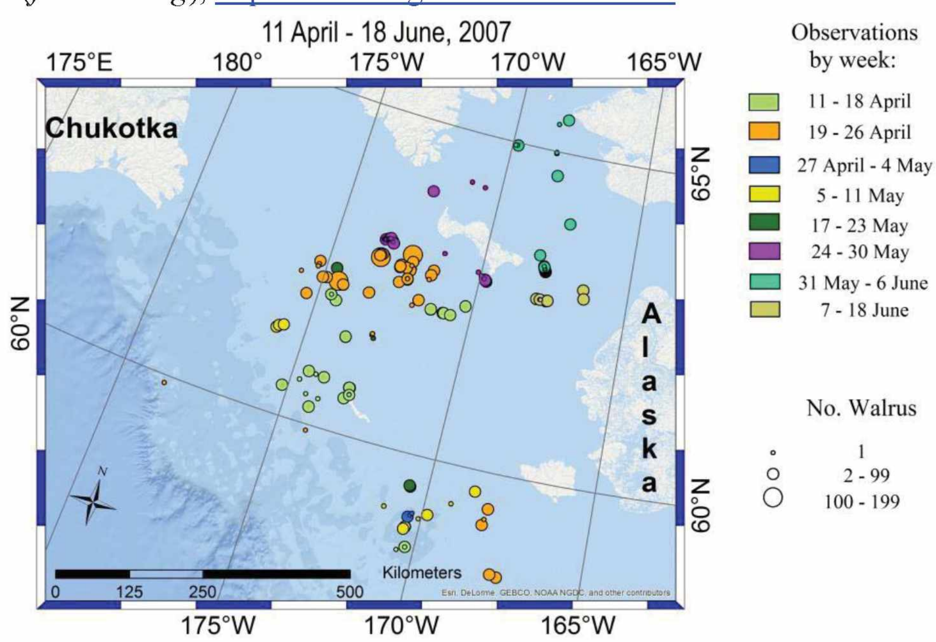

Figure 2.6 Ship-based walrus observations for 2007. Observations collected onboard the USCGC Healy in the Bering Sea during spring. Data were obtained from USCGC Healy cruises 07-01/02 and Ray et al. (*forthcoming*), http://dx.doi.org/10.1890/15-0430.1.

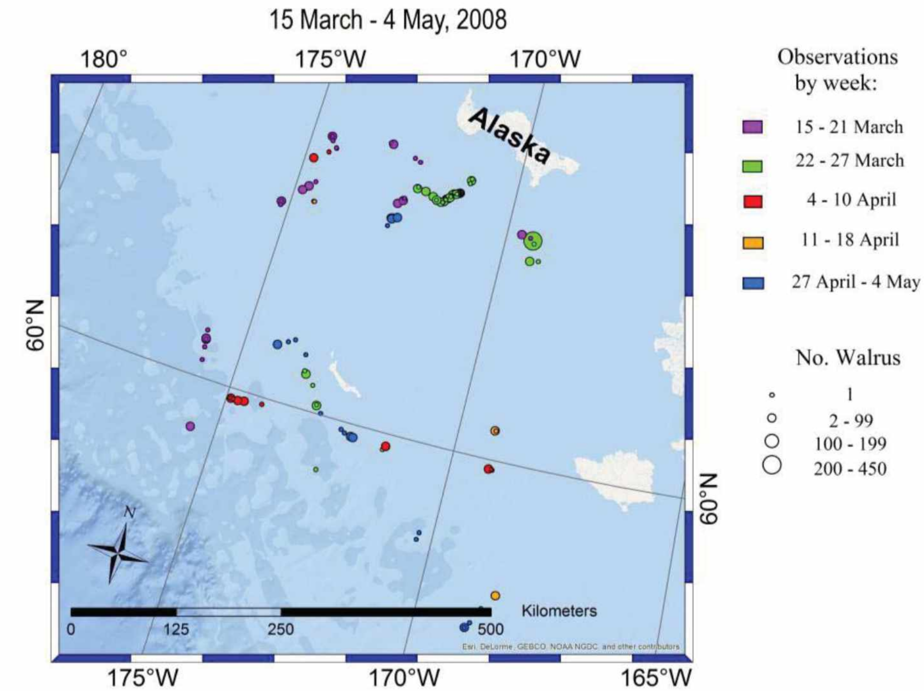

Figure 2.7 Ship-based walrus observations for 2008. Observations collected onboard the USCGC Healy in the Bering Sea during spring. Data were obtained from USCGC Healy cruises 08-01/02 and Ray et al. (*forthcoming*), http://dx.doi.org/10.1890/15-0430.1.

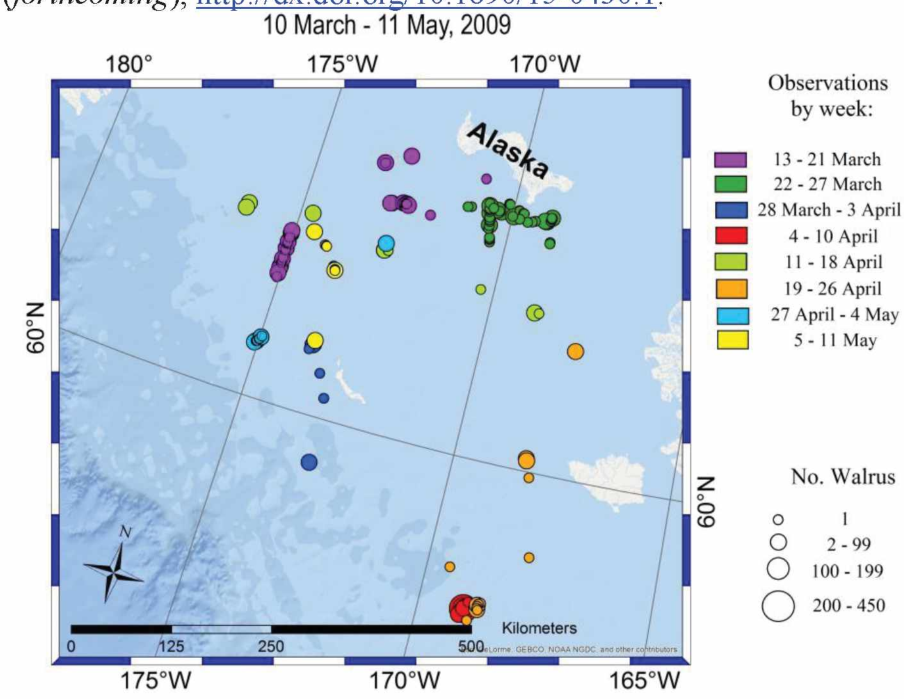

Figure 2.8 Ship-based walrus observations for 2009. Observations collected onboard the USCGC Healy in the Bering Sea during spring. Data were obtained from USCGC Healy cruises 09-01/02 and Ray et al. (*forthcoming*), http://dx.doi.org/10.1890/15-0430.1.

water. For some sightings in 2007 – 2009, the ice-observer included estimates of sea ice concentration and floe size. The ship-based surveys ranged over an area of 1,141,200 km^2 (Ray et al. *forthcoming*) and extended from the Bering Sea shelf break to the Bering Strait and from the Alaskan coastline to the edge of the international dateline. The ship-tracks cover between 2% and 3.8% of the total area of the Bering Sea shelf east of the international dateline. Real-time satellite imagery was used to direct helicopter flights to areas of likely ecologically-favourable ice conditions. Walrus observations are displayed in Figure 2.5 for 2006, Figure 2.6 for 2007 observations, Figure 2.7 for 2008 observations, and Figure 2.8 for 2009 observations.

Walrus observation locations in the seascape were found using the provided geographical coordinates and were projected into the Alaska-Albers Conical Equal Area projection, since this provided equal-area representation of the study region. In addition, all areas are proportional to the same areas on the Earth, distances are correct in both standard parallels, and the Alaska Albers Conical Equal-Area projection is the standard of, and has been adopted by, many state and federal agencies in Alaska for data integration concerns.

Since walruses were spread out across central and northern Bering Sea, a dataset that had complete coverage of the Bering Sea was required to complete the analyses. Data resolution was required to be higher in order to distinguish differences between various ice types and open water. Accounting for those ice features, such as leads, open water areas, and fragmentary ice arrangement also required high-spatial resolution. In order to describe the seascape surface of the Bering Sea, we devised an algorithm to quantify and classify a seascape-scale (100 km^2) area, distinguishable from other seascapes, using SAR. Since SAR data was not available for the walrus observations in 2009, these data were not able to be included in the subsequent analysis.

2.3.6 SAR data used for seascape classification

Mesoscale seascape classifications were created from SAR satellite data from the Canadian Space Agency's (2013) Radarsat-1 mission. These data were collected in the C-band wavelength in HH polarization, with a data resolution of 100 m. The data chosen were acquired in ScanSAR wide mode, covering an extent of 250,000 km^2, and covering the Bering Sea every 4 days, with a global orbit path repeat period of 24 days. Data are collected based on walrus observation availability during the period that the satellite was active and data were available (Table 2.6). Each level-1 SAR image was collected covering periods when sea ice was present over the Bering Sea shelf, typically from mid-October to late June (except in 2008, due to data availability).

Table 2.6 2006 – 2008 walrus observation and SAR image pairing statistics

	2006	2007	2008
Total walrus observations	118	197	130
Walrus observations matching SAR images	74	115	105
Walrus observations with matching SAR image but no matching classification	9	18	9
Total usable walrus observation-SAR image pairs	65	97	96

Images were downloaded from Alaska Satellite Facility's (ASF) Vertex data portal. ASF's MapReady Remote Sensing Tool was used to geospatially transform these data into the Alaska Albers Conical Equal-Area projection and export as amplitude images in floating-point GeoTIFF format. No terrain correction was performed and the amplitude data were not normalized to sigma-naught (backscatter cross-section) values since the processing effort incurred would have been substantial with a minimal impact on the results. For the mesoscale seascape classification of sea ice and ocean seascapes, statistical texture measurements were made on each SAR image. Textural analysis relies on the measurement of relative changes in pixel values within a local-neighborhood, rather than the absolute values of backscatter coefficient. SAR texture measurements are therefore relatively insensitive, for example, to the range-dependent variations in backscatter amplitude caused by changes in incidence angle. This allows the comparison of texture statistics across larger areas, or seascapes. Further details on the seascape classification algorithm are described in section 2.3.7. The GeoTIFF SAR images output from MapReady were despeckled using the Refined Lee's despeckle filter with default parameters in the Next European Space Agency SAR Toolbox (NEST), version 4C-1.1.

2.3.7 Seascape mapping of walrus habitat based on synthetic aperture radar imagery

While multi-thresholding was sufficient for an aerial imagery-based segmentation of different ice types and separation of open water, this was ineffective in classification of SAR data due to the complex nature of backscatter properties of various sea-ice types, as well as speckle inherent in SAR data. Therefore, in order to analyze SAR data for seascape mapping, we created a seascape-classification system that utilizes neighborhoods of backscatter measurements to calculate textural pattern through statistical texture analysis using gray-level co-occurrence matrices (GLCMs), which extends from work by Haralick, Shanmugam and Dinstein (1973), Shokr (1991), and Soh and Tsatsoulis (1999).

A GLCM is a matrix that describes the frequency with which particular values of paired pixels occur in a digital image. For a given GLCM, pixel pairs are defined as being any two pixels with a specified horizontal and vertical offset (alternatively defined by an offset distance, d, and direction, φ). For vertical and horizontal offsets of 1 pixel, there are four possible directions for φ: (0°, 45°, 90°, and 135°) and, corresponding directly to the east, northeast, north, and northwest direction from the initial pixel to the paired pixel, respectively. The size of the GLCM, and the computational effort required in its calculation, depends on the quantization level, G_q, or the number of different gray levels that the GLCM uses in its calculation of neighborhood pixel-pair occurrence. Lastly, the size of the neighborhood window, M, that the GLCM calculates co-occurrence over can vary depending on the application. For example, if a quantization level of 8 is chosen for the GLCM, then there will be eight separate gray-values in the image for the calculation of the co-occurrence matrix, even if the original image contains more than eight gray-values. Some images are able to have a reduced quantization level and still retain the textural information needed to describe the intended features. Increasing the quantization level increases the computation effort of the calculation. This matrix subset of the original image is analyzed for co-occurrence based on the number of quantization levels chosen for the algorithm.

Defined mathematically, the GLCM is the vector cross-product of the probability distributions of gray-level values for each possible pixel in the pairing. Thus, a GLCM of gray-values in a finite neighborhood is defined as a set G such that $p_i = \{1, 2, 3, \ldots, G_q\}$, $p_j = \{1, 2, 3,$

…, G_q}. This forms the co-occurrence matrix G: p_i x p_j, noticing that G is square. G is calculated such that p_{ij} consists of frequencies of distance d and gray levels i and j at pixel location (i, j) between neighboring gray-level pixel pairs in the original image subset M. The GLCM parameters include pixel pair distance, direction, quantization levels of the image subset, and window size. The maximum useable pixel distance, d, depends on the size of M in relation to the specific application, while φ can encompass a full 360° of rotation between pairs in discrete space. The GLCM is formed by calculating the occurrence of all possible pixel parings in M. For example, in a 2-bit image, we would see how many different neighborhood pairings there are in a 4x4 resultant GLCM. The GLCM tells us how many combinations of {(0, 1), (0, 2), …, (3, 3)} exist in the image in a certain discrete direction from the original pixel.

The size of the neighborhood window, M, effectively defines the resolution of the seascape classification derived from the GLCM results. In choosing the size of M, we considered walrus use of the sea ice at the seascape scale, in which they need to migrate across ~1,500 km from Bristol Bay to the Bering Strait, but also forage, rest, mate and give birth along the way. This required a window-size large enough that the textures of each seascape would be measureable and would coincide with McNutt and Overland's (2003) sea ice spatial scale transition to a plastic continuum, but small enough that yearly variation in these seascapes would not be lost due to a coarse-resolution. Since our seascapes encompass multiple floes, these floes cannot be treated as a group of individual particles, but as a continuous area of texture, containing floes and water. How these individual textural areas change over time requires that we scale these seascape classifications at or above the plastic continuum transition of sea ice. At a finer resolution, we are able to classify seascape changes that could show disconnect between various walrus observations, providing a more convincing preference for a particular seascape during their spring migration. For these reasons, along with processing effort considerations, M was chosen to be a 100 x 100 pixel neighborhood, encompassing 100 km^2 geographically due to Radarsat-1's pixel size after processing, which sits right at the transition point of McNutt and Overland's (2003) multi-floe and aggregate spatial scales into plastic continuum-driven ice deformation.

Table 2.7 Statistical texture equations and descriptions for SAR seascape classification

	Equation	Description
Arithmetic mean	$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i$	A measure of the average gray-value in each image subset window M
Standard deviation	$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2}$	A measure of the spread of gray-value across the image subset window M
Skewness	$S = \frac{E(x_i - \mu)^3}{\sigma^3}$	A measure of whether a distribution is "skewed" to one side or the other of the mean of the distribution in M
Kurtosis	$K = \frac{E(x_i - \mu)^4}{\sigma^4}$	Describes the peak shape of the distribution of the pixel values across the entire region of image subset M
Energy	$E = \sum_i \sum_j p(i,j)^2$	A measure of uniformity
Contrast	$C = \sum_i \sum_j p(i,j) * (\lvert i-j \rvert)^2$	Measures the intensity difference between the neighboring pixels
Homogeneity	$H = \sum_i \sum_j \frac{p(i,j)}{1+(i-j)^2}$	Calculates how similar each pixel pair in a region is
Autocorrelation	$U = \sum_i \sum_j p(i,j) * i * j$	Used to detect coarseness or fineness of the region
Dissimilarity	$D = \sum_i \sum_j p(i,j) * \lvert i-j \rvert$	A measure of contrast between pixel neighbors, highlighting differences
Entropy	$T = -\sum_i \sum_j p(i,j) * \ln(p(i,j))$	Measures the disorder in a region
Correlation	$O = \sum_i \sum_j \frac{p(i,j) * (i,j) - \mu_x * \mu_y}{\sigma_x * \sigma_y}$[1]	Measures how dependent pixel gray-values are to their neighbors.
Maximum probability	$MP = \sum_i \sum_j \max\{p(i,j)\}$	Measures how homogeneous areas of grey pixel neighbors are
Inverse difference	$ID = \sum_i \sum_j \frac{p(i,j)}{1+\lvert i-j \rvert}$	Measurement of low-contrast, high-ordered areas
Inverse difference normalized	[2]$IDN = \sum_i \sum_j \frac{p(i,j)}{1+\frac{\lvert i-j \rvert}{R}}$	Same to above Normalization assists in accounting for linear gray value structures that may arise from scene artifacts.

[1]Where $\mu_x = \sum_i \sum_j i * p(i,j)$, $\mu_y = \sum_i \sum_j j * p(i,j)$, $\sigma_x = \sum_i \sum_j (i-\mu_x)^2 * p(i,j)$, $\sigma_y = \sum_i \sum_j (j-\mu_y)^2 * p(i,j)$

[2]where R is a normalizing constant based on quantization levels chosen for the GLCM

Through analysis of each 100 km^2 region and its associated GLCM, we calculated 14 texture statistics (listed and defined in Table 2.7) with which to characterize the seascape within each 100 km^2 neighborhood. Using this approach, we take each 100 m-resolution SAR image and generate a 10 km-resolution 14-band texture image, which allows us to map the distribution of different winter and spring seascapes in the Bering Sea.

Since seascape classification is a recent application of remote sensing analysis, ground truth data for Arctic seascapes are unavailable for calibration and validation of seascape classifications beyond a manual, qualitative analysis. For this reason, we chose seascapes based on the six seascapes of the Bering Sea first defined by Ray and Hufford (1989) using MODIS imagery. By selecting a SAR mosaic of the Bering Sea that displayed all of Ray, Overland and Hufford's (2010) identified seascapes, we identified the corresponding neighborhoods in the SAR imagery.

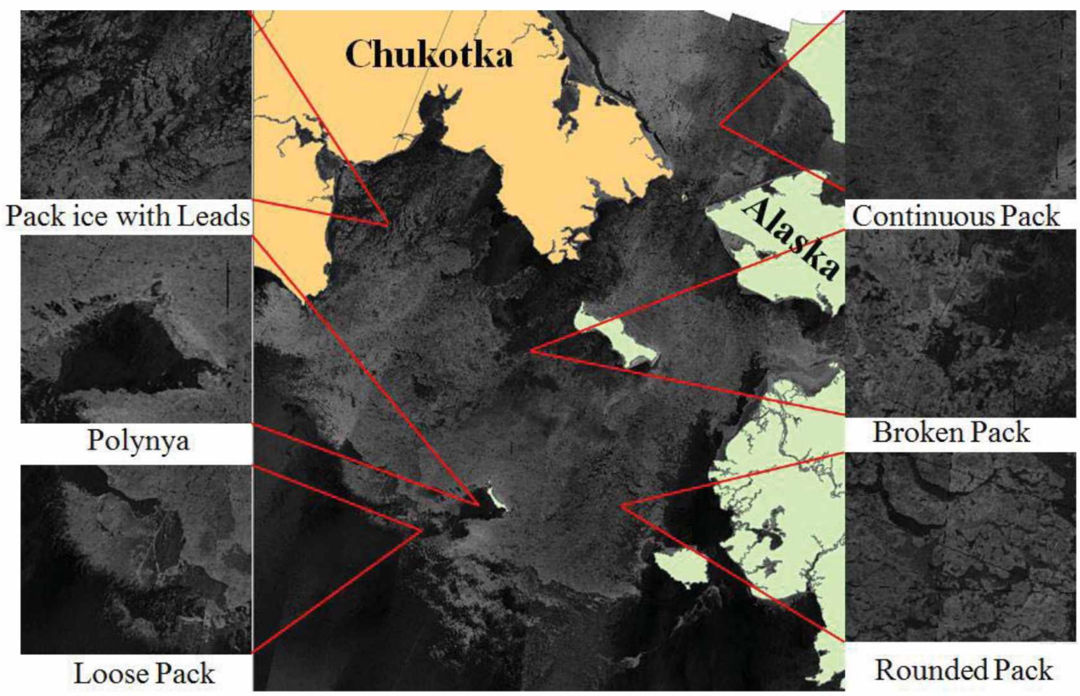

Figure 2.9 Seascape-scale ice features in SAR data. Mosaic of Radarsat-1 ScanSAR imagery, each covering an area of 250,000 km^2. The six seascape insets represent available seascapes in the Bering Sea during the spring melt and migration period of the walrus. Data for SAR mosaic constructed from available Radarsat-1 data from 20 – 27 April 2007. SAR data is courtesy of the Canadian Space Agency (2013) and the Alaska Satellite Facility. Radarsat-1 imagery © CSA 2007.

Each band in the 14-band texture images described above represents a different textural statistic. Principal component analysis (PCA) of various subsets of the multi-band texture images indicated that 7 components were required to explain 95% of the variance in the texture data. However, we found no simple correlation between any single texture statistic and any of these principle components. We therefore relied on a manual approach for selecting additional samples of SAR imagery matching Ray, Overland and Hufford's (2010) seascape definitions. We randomly-selected 100 SAR scenes and chose 50 subset image samples from those that visually matched the characteristics of each of the following six seascapes, adapted from Ray, Overland and Hufford (2010): (1) broken pack, (2) loose pack, (3) pack ice with leads, (4) continuous ice pack, (5) low-wind open water, and (6) wind-roughened open water. These six adapted seascapes were chosen based on distinctly identifiable regions of a typical Bering Sea SAR image, where 5 and 6 were needed to distinguish areas that were close in texture to 4.

The selection process described above yielded a total of 300 subset images, each of which was analyzed using all 14 texture statistics (Table 2.7) with the following parameters: d = 1 through 25, all four discrete directions ($\varphi = \{0°, 45°, 90°, 135°\}$), and a quantization $G_q = 64$. We chose $G_q = 64$ since the computational demand of higher quantization levels does not produce significant improvement in texture statistics analysis. Each mean value of the texture statistics for each seascape listed above were plotted and visually-compared with each other to determine clustering of individual classes, dependent on pixel displacement and quantization as well as the various statistical texture measurements described in Table 2.7. Classes 1, 2, and 3 clustered distinctly and separately from classes 4, 5, and 6 only when using the correlation texture statistic and displacements 1 – 25 (Figure 2.10c). For all 14 texture statistics, of which a select number are shown in Figure 2.10, we calculated the average of each 2nd order texture statistic and correlation (c) was the only texture that had a clear separation between these two clusters of classes. We conclude that, at this stage, textural analysis of SAR imagery can only reliably identify two broad classes of seascape, which are herein referred to as fragmented pack (composed of seascapes 1, 2, and 3) and homogeneously textured ocean and ice (composed of seascapes 4, 5, and 6).

In order to automate the process of identifying regions of fragmented pack and homogenously textured ocean and ice, we developed a training and testing procedure using the 300 manually-selected seascape subsets. Classification rules were created from these two broad seascape definitions. For each image subset, we calculated the correlation texture statistic using results from GLCMs in four directions ($\varphi = \{0°, 45°, 90°, 135°\}$), which were then averaged. These were then used as baseline data for each seascape definition. The training and testing algorithm calculated variation in false positives and false negatives for pixel displacements 1 – 25 and for a quantization of 64. Two-thirds of the seascape subset images were chosen randomly for training, and the remainder subsets were used for testing for classification rules. Regions with a correlation statistic in the range 0.25966 – 0.7286 were classed homogeneously textured, while regions with correlation values outside of this range were classified as fragmented pack. These rules, calculated from each training set and consisting of variance in the correlation texture statistic of the GLCM results, were used in order to evaluate false-positive and false-negative rates of classification of the subsequent testing set. This classification algorithm agreed with our interpretation of the seascape 96.5% of the time for averaged fragmented pack ice, homogeneously textured ocean, and ice seascapes overall (Figure 2.11). While this classification error of 3.5% is low, a 2-class algorithm distinguishing homogeneous and heterogeneous correlation textures would be less-difficult to correctly classify than seascapes that have closer neighborhood texture signatures. The maximum true-positive rate of classification was obtained for both seascape definitions at a pixel displacement of 11, the highest reliability for the average of both seascape classification results.

Geospatial and instrument error, including projection error, SAR sensor error, speckle artifacts and distortions in the SAR data all can play a role in an incorrect classification-observation pairing on which to base the walrus preference to a particular seascape. While every walrus-classification pair was manually examined, those SAR classifications that were used to quantify the fragmented pack ice seascape's evolution through spatial and temporal dimensions were not completely checked manually. Thus, these artifacts, speckle and noise that may have been missed by the despeckle filter, and geometric errors can alter the ability to successfully measure a single seascape's area, both relative and absolute. In addition, the SAR seascape algorithm's accuracy leads to a number of classification errors due to an imperfect training and testing accuracy. This would account for up to 10,580 km^2 of classification error (with a 5% misclassification rate and an average of 2,116 possible per-image classification windows, 46 classification windows length and width; *see* section 2.3.6) per SAR image. Despeckle processing errors, geometric artifacts, and misclassification caused by high-wind roughened seas in the original SAR data can produce an error in relative and absolute seascape measurements, typically on the order of a low number of classification windows. Thus, there would have to be at least 110 classification windows that contained noise- laden artifacts or processing or geometric errors in order for the accuracy to exceed the classification error of the algorithm itself.

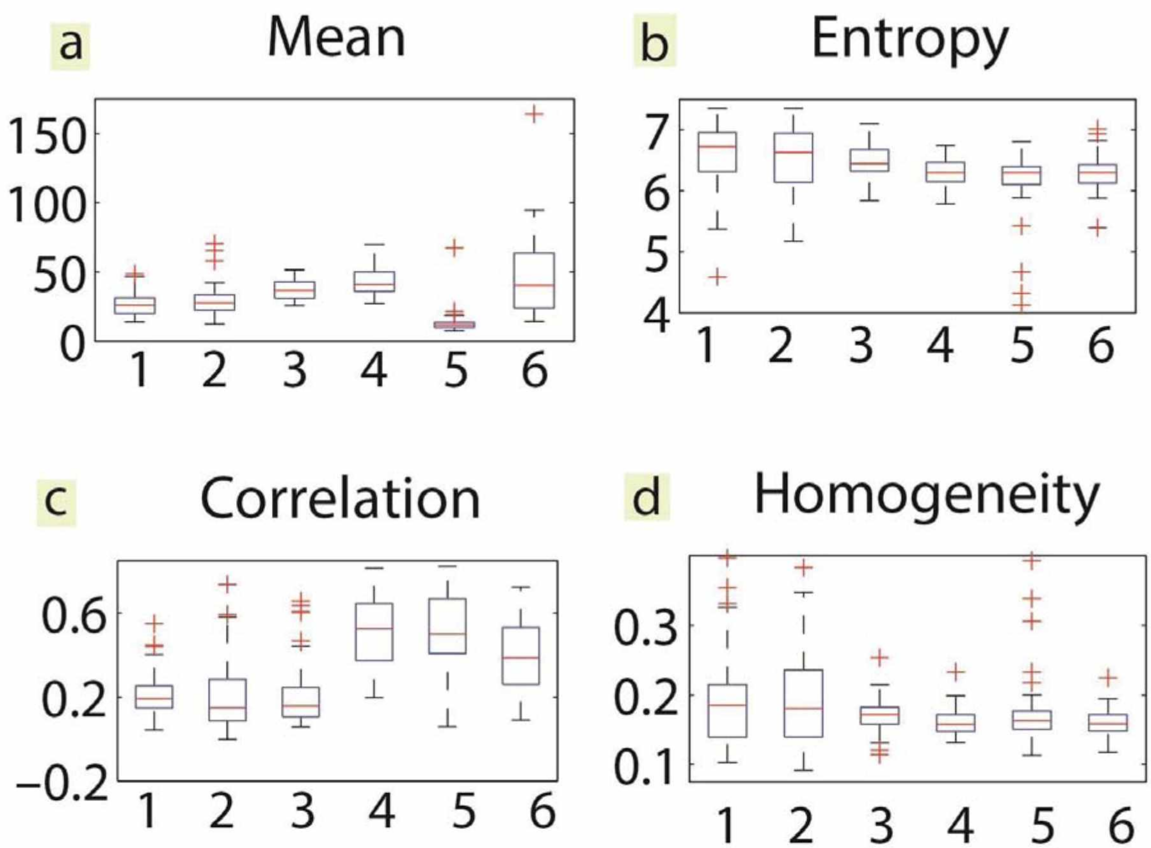

Figure 2.10 Box and whiskers plot of select texture statistics. These statistics were considered in the SAR seascape classification algorithm. Out of a – d texture statistics, where (a) encompasses a 1st order texture and (b) – (d) are 2nd order texture statistics, the only clear distinction between the 'fragmented' classes (1-3) and the 'homogeneous' classes (4-6) comes from the range of the 25 – 75 percentile for correlation (c).

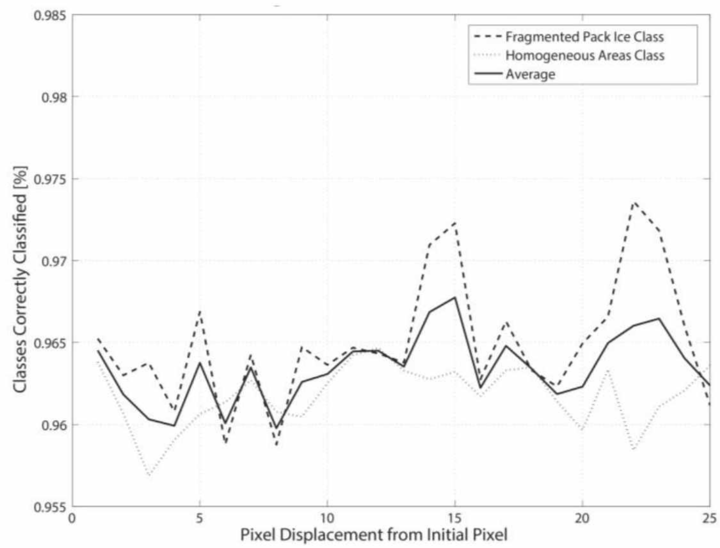

Figure 2.11 Results of training and testing of the 2-class SAR classification algorithm. Fragmented pack ice was correctly classified the highest percentage, while the homogeneous area classification reliability varied less sporadically.

2.3.8 Use of National Ice Center data in seascape analysis

In their standard ice chart products, the U.S. National Ice Center (NIC) adopts the WMO "egg code" symbolism for defining the characteristics of sea ice within areas of largely uniform composition. The egg code defines the overall ice concentration and the relative fractions of up to three primary classes that make up the ice cover in any given region. NIC's collaboration with the WMO was formed to preserve and digitize ice chart data for research purposes. Through this collaboration, WMO Sea Ice Grid (SIGRID) codes and fields, which consist of total ice concentration, partial ice concentrations of thickest to thinnest ice types (all reported in tenths), ice development stages (WMO section 2), and predominant ice forms (WMO sections 2 and 4), were created for the national ice center for the creation of new, digitized ice charts for navigational, planning, and scientific purposes. Ice charts are currently produced using data from in-situ measurements, remote sensing (which may include ENVISAT, DMSP OLS, AVHRR, MODIS, QuickSCAT, DMSP SSM/I, and Radarsat satellite data as well as foreign ice charts), and model analyses to create a weekly or bi-weekly ice chart for the Arctic and Antarctic, climatologies and forecasts, and daily ice-edge products. NIC ice edge products have a higher accuracy than SSM/I passive microwave data due to their higher-resolution source data (National

Ice Center 2006). Ice charts are important products for navigational and operational planning activities in ice covered waters. Thus, particular attention was paid to ice edge location by NIC analysts, which creates a superior product at the ice edge, but can be lacking in precision in the high Arctic where there are fewer human activities (National Ice Center 2006). NIC ice edge Shapefiles were used to clip fragmented pack seascape Shapefiles at the ice edge to reduce the number of false positives in open water areas below the NIC-defined ice edge.

2.4 Results

2.4.1 Evidence for walrus patch-scale habitat preference

Walrus observations for the 2012 aerial survey contained evidence of many key life cycle events, including births and calf-rearing (Figure 2.2). The number of observations where YOY were present (n = 24) was almost 10% of the entire observational dataset. This provided an opportunity to study ice-patch descriptors that may be important to adults and YOY, which may differ from those of adults and juveniles due to the YOY's inability to withstand cold water temperatures for long periods of time. The main distinction between walruses during the spring migration is segregation by sex and age, where males mainly stay in the Bering Sea and utilize land haulouts and females and YOY head north to the Chukchi Sea in order to summer on the remaining sea ice as long as possible. We were unable to distinguish walrus sex and specific age in these aerial photo data. Our distinction, then, is based on walrus size extremes to distinguish observations of YOY. High-frequency areas for observations of YOY walruses are near St. Lawrence Island and Nunivak Island in late April and early May, but sampling bias precludes us from further specificity. Thus, we define three classes of walrus occupation:

1. Occupied: any ice patch with a walrus present
2. Adults: those ice patches occupied by adult and juvenile walruses with no calves present
3. Adults and YOY: those ice patches with at least one walrus calf present.

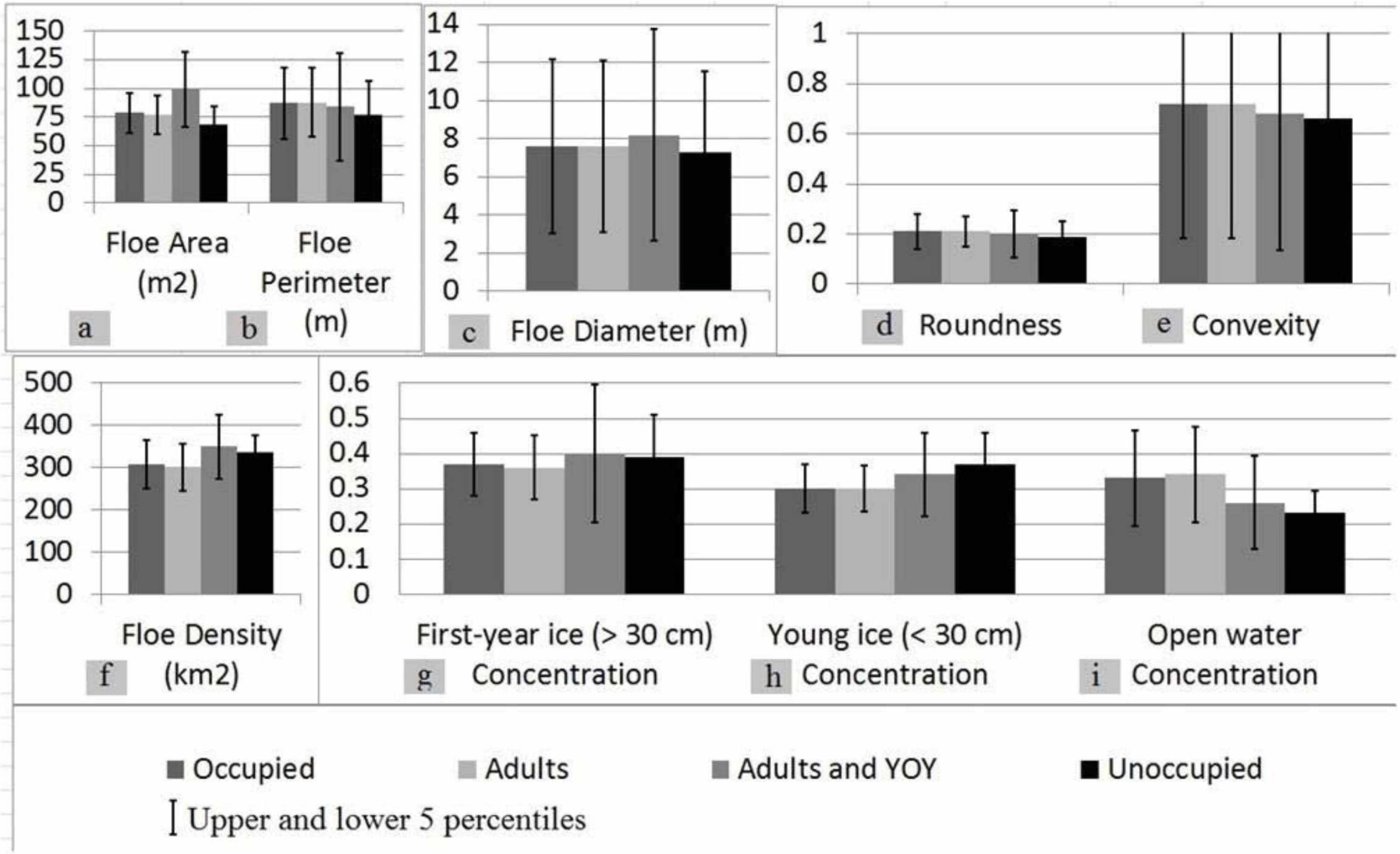

Figure 2.12 Mean and 5% percentiles of occupied-unoccupied classes. Walrus occupied, adults and juveniles, adults and YOY, and unoccupied sea ice size, shape, and arrangement descriptors are compared based on mean and 5 percentiles.

All ice-patch descriptors being compared here were tested for normality using the Kolmogorov-Smirnov test. Non-parametric statistical methods are useful when the distribution shape of the data is not known. This method examined whether samples had come from the same or different statistical distributions. In order to compare each class of data in relation to the other classes (e.g. ice patches containing adults and YOY vs. ice patches containing adults and juveniles), we use the results of our non-parametric test through a post-hoc test, which is considered a method of multiple comparison procedures. This test allows us to find significant differences between pairs of classes, reducing the chance of finding an insignificant difference due to the number of comparisons, when compared to the t-statistic for mean comparison. Normality was rejected at the 5% confidence level for each ice-patch descriptor. This suggested that non-parametric statistical tests, like Welch's ANOVA, and its associated Games-Howell post-hoc test for significance, should be used to examine which sample sets are significantly different from each other. For equally-spread data distributions in a group, that group was said to be non-heteroscedastic, and vice versa. Each ice-patch descriptor, using Levene's test for equal variances, showed heteroscedasticity. Thus, Welch's ANOVA, and the associated Games-Howell post-hoc test, was used for all occupied and unoccupied ice-patch sample sets.

All ice patches with walrus observations (Figure 2.2) were compared with ice patches unoccupied by walruses. These areas, focusing on nine separate geomorphometric ice-patch and floe descriptors (floe area, diameter, perimeter, roundness, convexity, percentage of first-year ice, young ice, and water cover, and the floe density per unit area), show significant difference (degrees of freedom (df) = 3, $0 \leq p \leq 1.7 \times 10^{-5}$) across all comparison classes (occupied, unoccupied, YOY present, and adult-occupied ice patches). Using the Games-Howell ad-hoc test (herein, referred to as an ad-hoc test), we found that area, perimeter, diameter, roundness and first-year ice concentration patch-scale descriptors in occupied ice patches showed no statistically significant differences from those in unoccupied ice patches. Significant differences in floe convexity, young ice and open water concentrations, and floe density, between occupied and unoccupied ice patches indicate that ice patches occupied by walruses exhibit a preference for floe arrangement, and possibly shape, in a local-scale area during their migration and feeding-resting cycles.

The data distributions of floe convexity, open water concentration, and floe density appear variable in kurtosis, mean, and skew between occupied and unoccupied ice patches. These data distributions are unimodal, just like the unoccupied ice-patch measurement of the same descriptor. Young-ice concentration, however, is a bimodal distribution for ice patches that are walrus-occupied and adult with juvenile-occupied, with modes centered on 10% and 50% concentration. Unoccupied ice patches, on the other hand, are show a much wider and more uniform distribution with a mode centered on 55% young-ice concentration.

Comparing the distribution means for each texture statistic, our results suggest that occupied ice-patches are more likely to have lower concentration of young ice and higher open water concentration than unoccupied ice-patch areas, shown in Figure 2.12 (h,i). Ice patches occupied by adult walruses show 10% more open water concentration, on average, than unoccupied ice patches or those occupied by adults with YOY (Figure 2.12i). This is offset by a lower mean first-year ice concentration (Figure 2.12g). Overall, ice patches occupied by any walruses tend to be composed of floes that are larger in floe size, a convex floe shape, and have less ice concentrations (first-year and young ice), showing a preference for areas of higher open water concentration. By comparison, unoccupied ice-patches that we analysed were more-likely to contain a higher floe density (per km^2), smaller and less convex-shaped floes, and have a higher concentration of sea ice, with an average of 77% concentration of ice (Figure 2.12a-i). Ice patches occupied by adults and YOY did not exhibit significantly different distributions for any descriptors when compared to unoccupied ice patches. Walruses accompanied by YOY show an apparent preference for lower open-water concentrated ice patches, favoring higher first-year and young ice concentration (Figure 2.12g-i). Ice patches with adults and YOY present also displayed larger floes (by area and diameter) and more first-year ice floe density (Figure 2.12 a,c,f). Since edge floes were not included in the area and density calculations (Figure 2.12 a,f), these results do not fully represent first-year ice concentration (Figure 2.12 g), which was calculated from the overall image first-year ice cover, including edge floes. Since these edge floes sometimes cover a large area of an image, these would skew the mean floe size, shape, and density descriptor statistics for typical aerial images. Thus, ice concentration is representative of an entire image concentration, while specific floe means represent those floes that could be reliably geomorphometrically measured in each image with respect to size and shape.

2.4.2 Regional variability of ice-patch descriptors in the Bering Sea

The spatial variability of sea ice in the Bering Sea during the spring migration of walruses and the melt season of the sea ice can show sub-regional variations with respect to ice-type, weather and ocean forcing effects, ice age and distribution, and floe sizes and shapes. In order to determine whether specific areas of the Bering Sea are persistently or sporadically similar to those descriptor properties that are preferential to walruses (see 2.4.1), we devised eight separate sub-regions in the Bering Sea. These exploratory methods are used to determine whether the Bering Sea ice displays areas of discrete ice-patch descriptor properties during the spring melt and migration period.

Local experts from communities who hunt walruses for their subsistence and livelihood have observed what is described as multiple populations of the Pacific walrus that migrate north from both the east and western side of St. Lawrence Island during spring (Krupnik and Ray 2007). Based on traditional knowledge observations, island location, land boundaries, and the spatial distribution of walrus observations from the 2012 NOAA BOSS dataset, we defined eight sub-regions of the Bering Sea shelf (Figure 2.13). The southern extents of sub-regions 2, 5, and 8 are defined by the 200 m isobath of the Bering Sea shelf, while the northern boundary for 1 is the Bering Strait division between the Bering Sea and the Chukchi Sea at 65° N latitude. Sub-region 2 is not used in these analyses due to NOAA BOSS flights being conducted on the eastern side of the Bering Sea shelf only. These sub-regions of the Bering Sea (Figure 2.13) were used as boundaries for assessing spatial variability in ice-patch descriptors throughout the spring-melt season. Walruses identified from the NOAA BOSS imagery were located in sub-regions 1, 3 – 8.

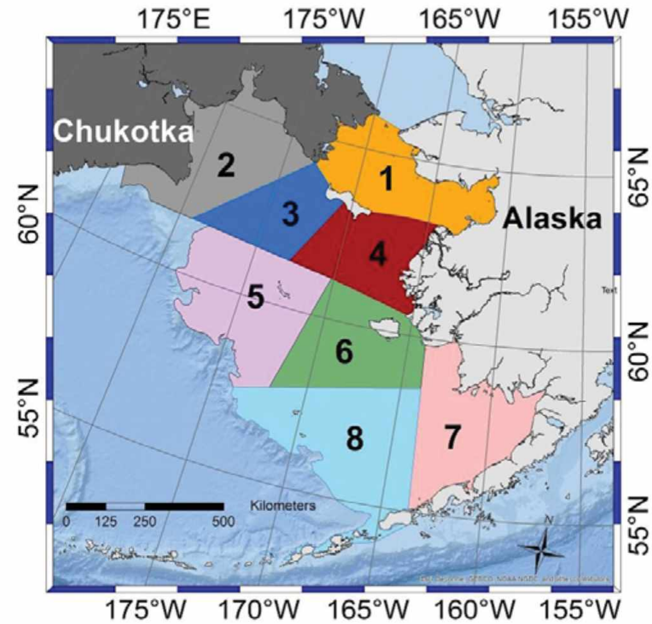

Figure 2.13 Sub-regions of the Bering Sea. Sub-regions numbered 1 – 8 correspond to: (1) North of St. Lawrence Island, (2) Anadyr, (3) Southwest of St. Lawrence Island, (4) Southeast of St. Lawrence Island, (5) St. Matthew Island, (6) Nunivak Island, (7) Bristol Bay, and (8) the Pribilof Islands.

Using the results of the post-hoc test (*see* section 2.4.1), we compare sub-region to sub-region to determine consistency or variance. The distributions of descriptors floe convexity and roundness, as well as concentrations of young ice and open water suggest that the sub-regions 1, 3, and 4 have similar ice descriptor properties. Sub-regions 5 and 6 have no significant differences across all ice-patch descriptors except first-year ice concentration, which would suggest that they have similar ice-patch descriptors also. Lastly, sub-regions 7 and 8 have similar distributions for floe area and diameter, but do not have similar distributions for all other ice-patch descriptors. Using these results, along with the mean distribution results (Figure 2.15), we have combined sub-regions into three spatially-explicit *zones*: sub-regions 1, 3, and 4 are the *northern zone*, sub-regions 5 and 6 are the *central zone*, and sub-regions 7 and 8 are the *southern zone* (Figure 2.14).

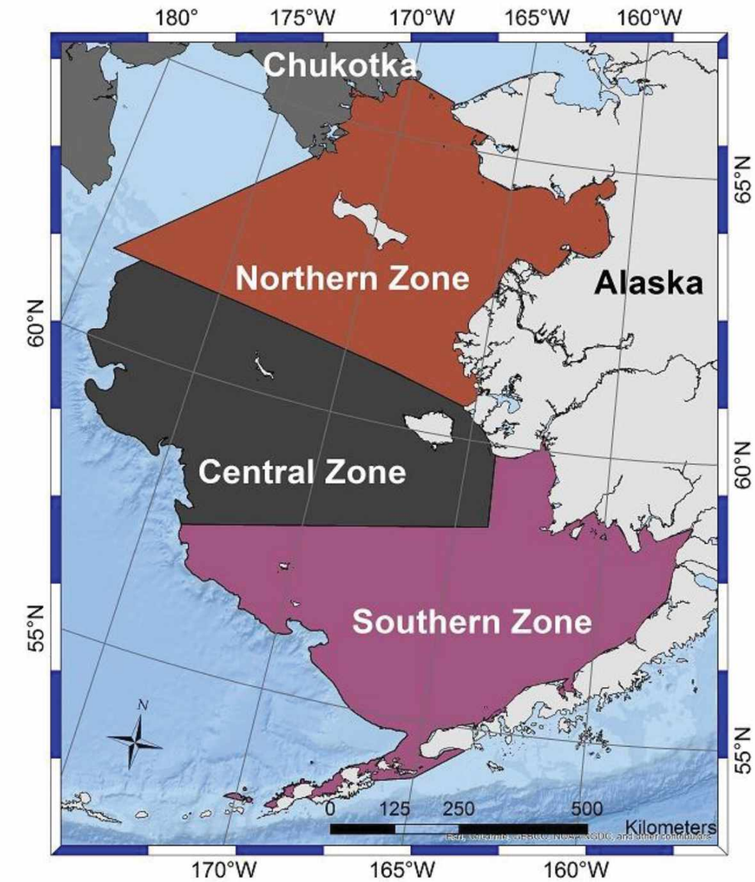

Figure 2.14 Zones of the Bering Sea. Zonation follows from similar ice-patch descriptors between sub-regions.

The strongest evidence of zonation is found in floe convexity, floe roundness, floe area, and open-water concentrations. Floe convexity is unimodal in each region except the area surrounding St. Matthew Island (5). Mean convexity increases in ice patches from the northern zone to the southern zone (Figure 2.15). This shows that floes are least rounded and convex in the northern zone and round out, through deformation and spring melt processes, towards the southern zone, which has the most rounded floes. Young-ice concentration and floe density also decrease from the northern to the southern zones, while open water concentration increases in this direction. Mean open water concentration for ice patches in sub-regions 1, 3, and 4 is 10 percentage points below that in sub-region 6, 7, and 8. Young ice concentration is much higher in sub-regions 1, 3, and 4 than in sub-regions 7 and 8, especially in sub-region 8, where the mean young ice concentration is double. Floes are largest in mean area and diameter in sub-regions 5 and 6.

Table 2.8 Welch's ANOVA p-value and post-hoc test. Comparison of results between walrus adult-occupied ice patches and sub-region specific ice patches. P-values reported for adult walrus-occupied groups compared to each sub-region in the Bering Sea. Numbers 1 and 3 – 8 correspond to sub-regions defined in Figure 2.11. WA represents ice patches occupied by walrus adults. FYI, YI, and OW are first-year ice concentration, young ice concentration, and open water concentration, respectively. S represents significant differences as determined by the post-hoc test, while NS designates non-significant differences between classes.

	Area	Perimeter	Diameter	Convexity	Roundness	FYI	YI	OW	Density
p	2.0×10^{-6}	3.6×10^{-23}	3.0×10^{-5}	[1]0	[1]0	[1]0	[1]0	[1]0	6×10^{-34}
1-WA	NS	NS	S	S	S	S	S	S	S
3-WA	NS	NS	NS	S	S	NS	S	S	NS
4-WA	NS	NS	NS	S	S	NS	S	S	S
5-WA	NS	NS	NS	S	NS	S	S	S	NS
6-WA	NS	NS	NS	S	NS	NS	S	NS	NS
7-WA	S	S	S	NS	NS	NS	S	NS	S
8-WA	NS	S	NS	S	S	S	S	NS	S

[1]Due to large sample size, these p-values are essentially zero for the Welch's ANOVA.

Comparing those ice-patch descriptors important to walruses with results of the sub-region analysis of ice-patch descriptors, ad-hoc test results suggest Nunivak Island sub-region has the least significant differences for walrus-occupied ice patches and region-specific ice patches across the Bering Sea shelf. Significant differences exist only for convexity and young-ice concentration in those ice patches occupied by adult walruses. Each other sub-region shows significant differences for floe shape and first-year, young-ice, and open water concentrations (Table 2.8).

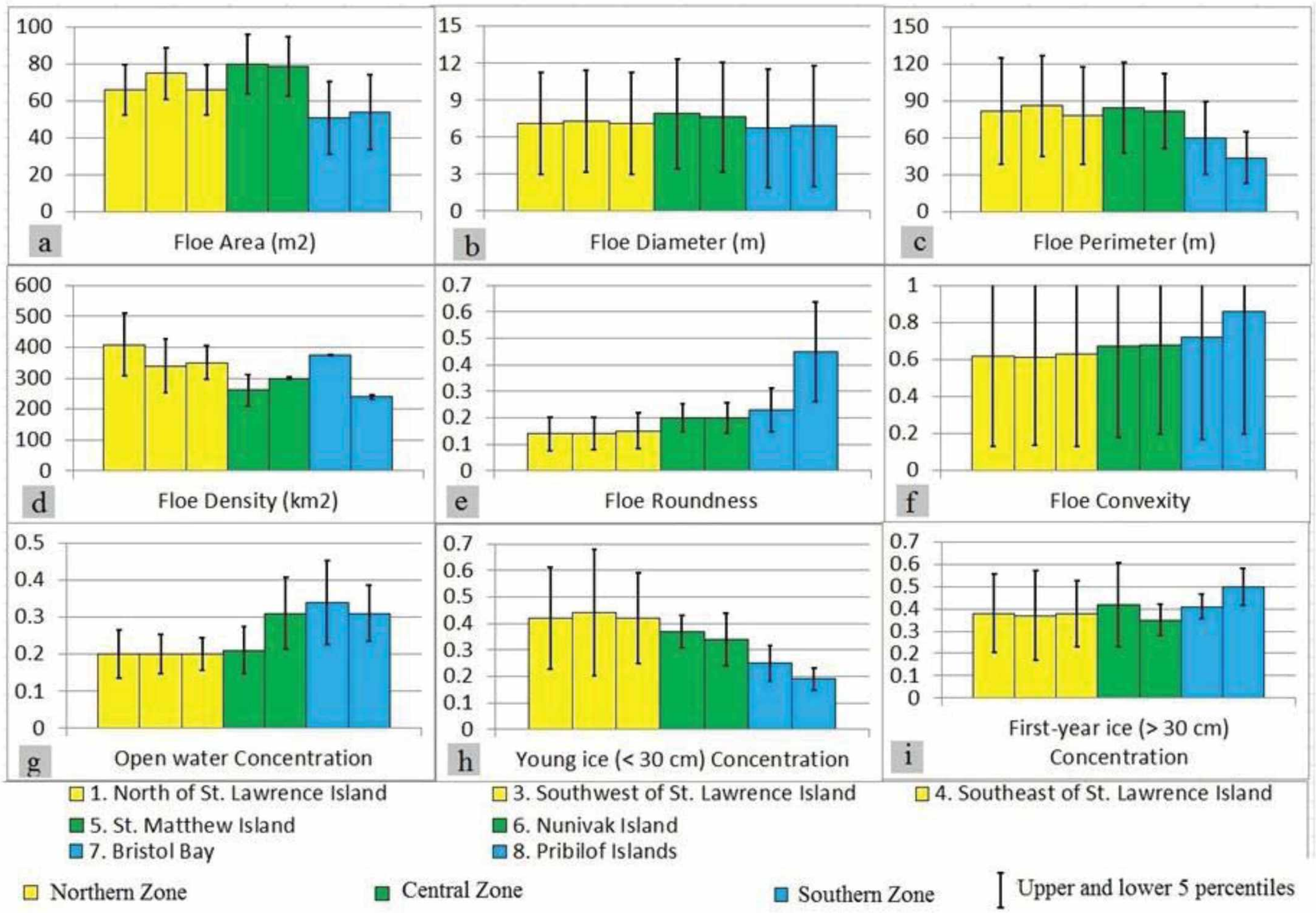

Figure 2.15 Mean and 5% percentiles of Bering Sea sub-regions. Sea ice descriptor means and 5% percentiles. Yellow denotes northern zone sub-regions (north, southwest, and southeast of St. Lawrence Island), green denotes central zone sub-regions (St. Matthew Island and Nunivak Island), while blue denotes southern zone sub-regions (Bristol Bay and the Pribilof islands).

2.4.3 SAR-derived seascapes in the Bering Sea

From the texture-based classification of SAR imagery (section 2.3.7), the seascape we define as fragmented pack is widespread throughout the Bering Sea, though it is more persistent throughout the seasonal cycle around the coasts and southern margins of the ice cover, including the Bering Strait (Figures 2.176 – 2.18). Due to difficulty distinguishing open water from homogenous sea ice, we used ice chart data from the U.S. National Ice Center to delimit the southernmost extent of sea ice (*see* section 2.3.8). This allowed us to calculate the fraction of the ice cover in the Bering Sea that was composed of fragmented pack for each 4-day period (the temporal period in which a complete SAR mosaic covered the entire Bering Sea). Areas that did not fit the classification rules for fragmented or homogeneous seascapes were excluded from this analysis. Unclassified areas account for 14% of SAR data analyzed.

For each year walrus observations were available (2006, 2007, and 2008) from the Healy cruises in the Bering Sea (*see* section 2.3.5) and co-located with available SAR data, fragmented pack ice area and seascape maps were created for each 4-day mosaic. Each year varied in coverage and extent of the Bering Sea, and a select set for each year is presented in Figures 2.1716, 2.17, and 2.18. Fragmented pack seascapes in 2006 typically were present in the central and northern Bering Sea, from St. Matthew and Nunivak Island, north to the Bering Strait, Gulf of Anadyr and Norton Sound (Figure 2.17). While 2006 and 2007 provided a look at fragmented pack coverage through the end of spring, 2008 lacked this coverage since data after May 2 was unavailable. Fragmented pack seascape patch area for 2007 behaved in a similar way for the month of May into mid-June. April saw fragmented pack ice seascape in Bristol Bay and near Nunivak Island. Late in the season, in June, fragmented pack persisted near St. Lawrence Island and St. Matthew Island. Typically, fragmented pack ice was present southwest of St. Lawrence Island and in the Gulf of Anadyr until early June, providing potential platforms for walruses still migrating to the north or to land haulouts (Figure 2.16). In 2006 (Figure 2.17), fragmented pack ice is absent in the southeastern region of the Bering Sea (in Bristol Bay). Ice was virtually absent in the Bristol Bay area during the month of May and early June, as 2006 was a transitional year from a warm to a cold period with swift melting occurring in April (Ray et al. *forthcoming*).

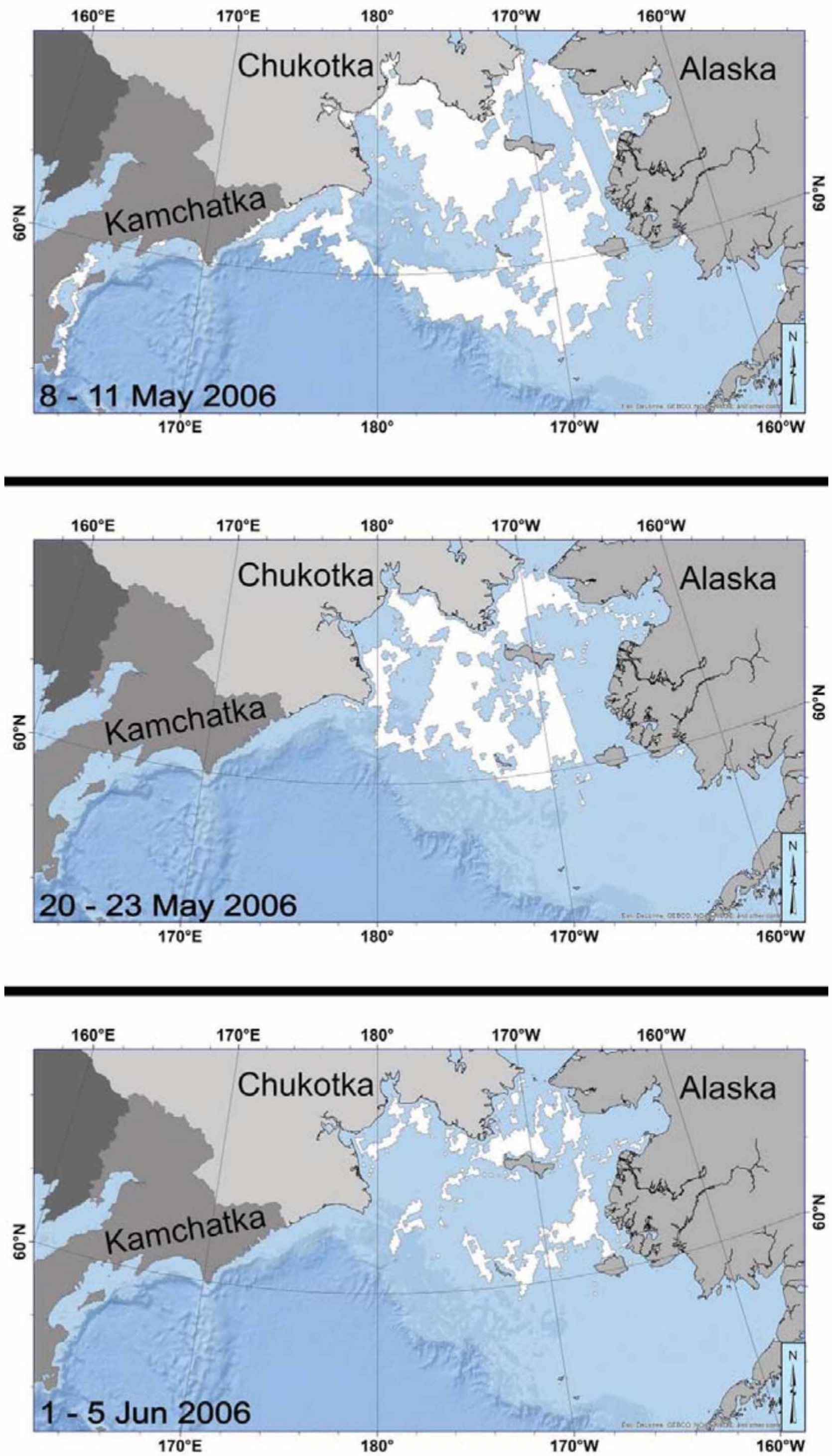

Figure 2.17 Fragmented ice pack seascape change during the 2006 melt season. White denotes areas of fragmented pack ice seascape.

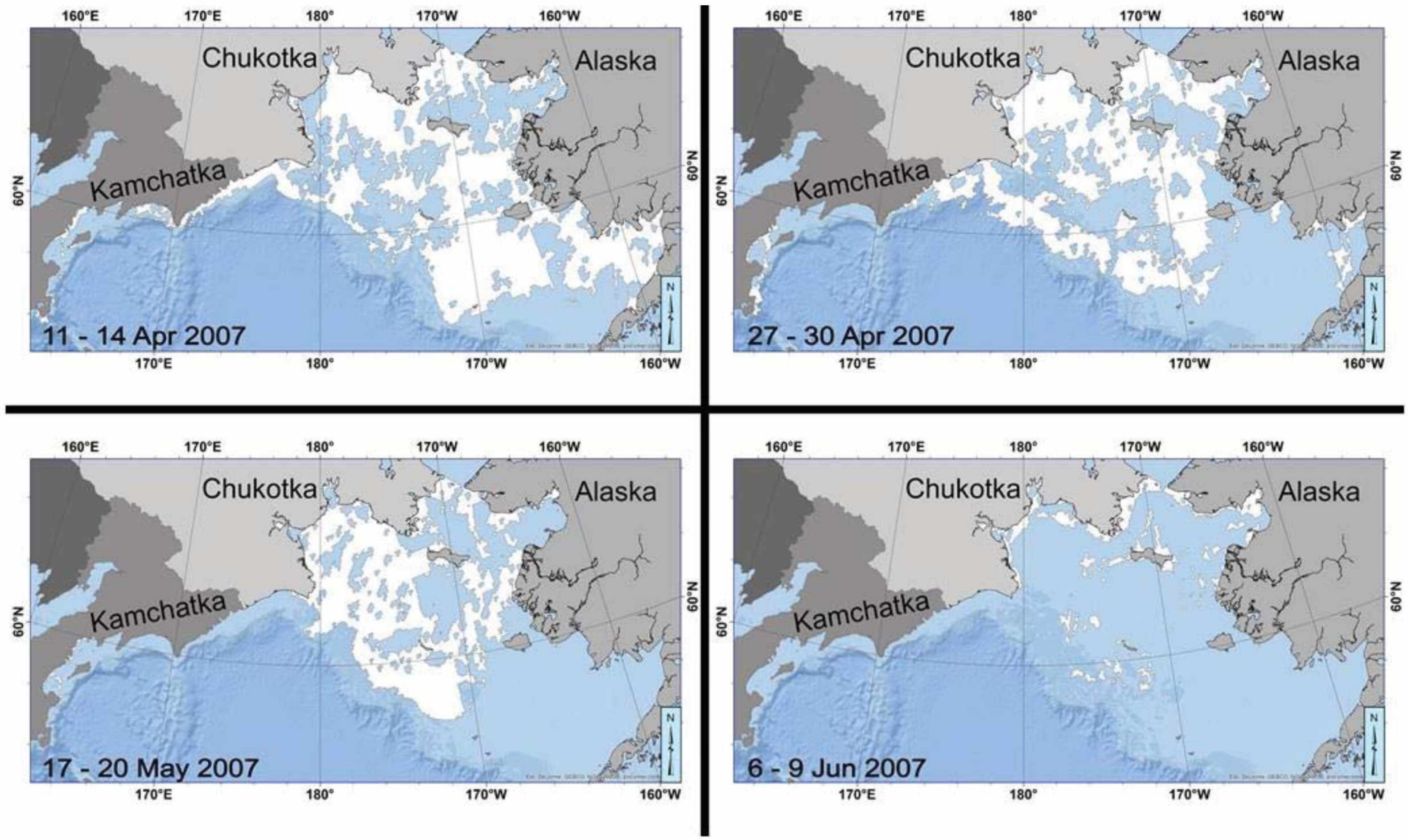

Figure 2.17 Fragmented ice pack seascape change during the 2007 melt season. White denotes areas of fragmented pack ice seascape.

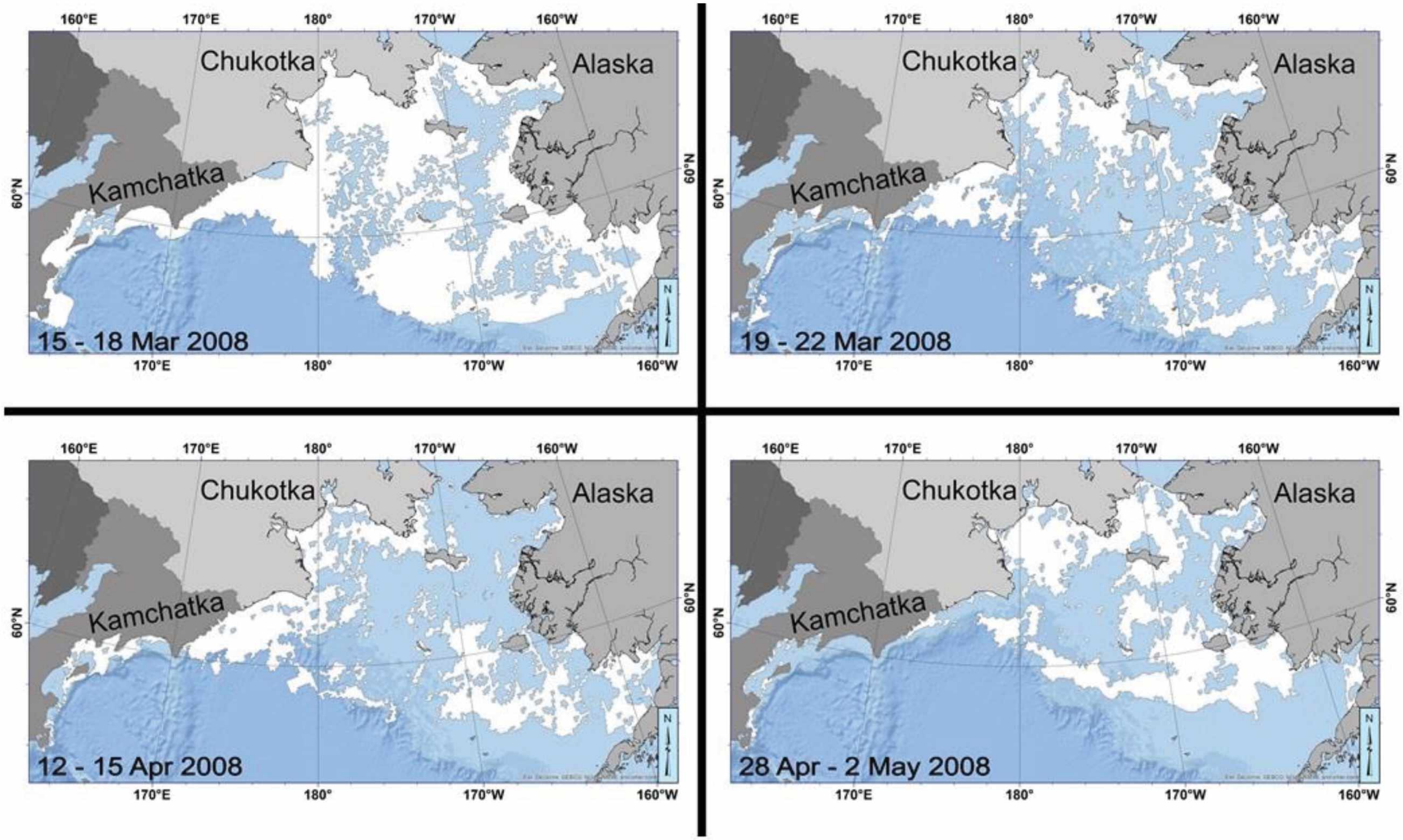

Figure 2.18 Fragmented ice pack seascape change during the 2008 melt season. White denotes areas of fragmented pack ice seascape.

In 2007, sea ice transitioned to a cold period, leading to a heavy ice year. Fragmented pack ice was present in Bristol Bay until early May. Remnant ice persisted around St. Lawrence Island, St. Matthew Island, and coastal areas of the Gulf of Anadyr until after mid-June, verified by manual SAR interpretation. Bering Sea ice cover was heavy in 2008 due to cold northerly winds persisting through the spring (Ray et al. *forthcoming*). Earlier in the year, during the transition from winter to spring in March, the absolute area of fragmented pack ice reduced by almost half between March 15 and March 22, most likely due to freezing and congelation of sea ice into a continuous pack in 2008. On March 31, sea ice extent reached its maximum for the winter (Ray et al. *forthcoming*), while fragmented pack was prevalent in the Gulf of Anadyr and Bristol Bay, as well as south of St. Lawrence Island (Figure 2.18). Fragmented pack ice occupied the southeastern and southwestern regions of the Bering Sea shelf, as well as the Gulf of Anadyr throughout the 2008 study period into early May. The central Bering Sea shelf began to experience fragmented pack seascapes at the end of April, beginning the retreat northward into May.

Fragmented pack seascapes as individual, separate seascape patches exhibit a moderate increase in mean seascape patch area, tripling briefly in mid-May, and rapidly decreasing by mid-June. Average fragmented pack patch area increased through March 30th, 2008 (Figure 2.19), due to connection of fragmented pack patches at this scale and coalescence of patches into continuous ice at ice extent maximum. The mean seascape patch area maximum in mid-May occurs conceivably due to rapid ice melt and breakup traveling through the Bering Strait.

Absolute area of all fragmented pack ice in the Bering Sea shows a declining trend, similar to the total potential ice area through mid-June. Mean decrease in total fragmented pack ice area was over 10,000 km^2 per day, while monthly rates ranged between 9,000 and almost 13,000 km^2 per day, with largest rates occurring in March and May (Figure 2.20).

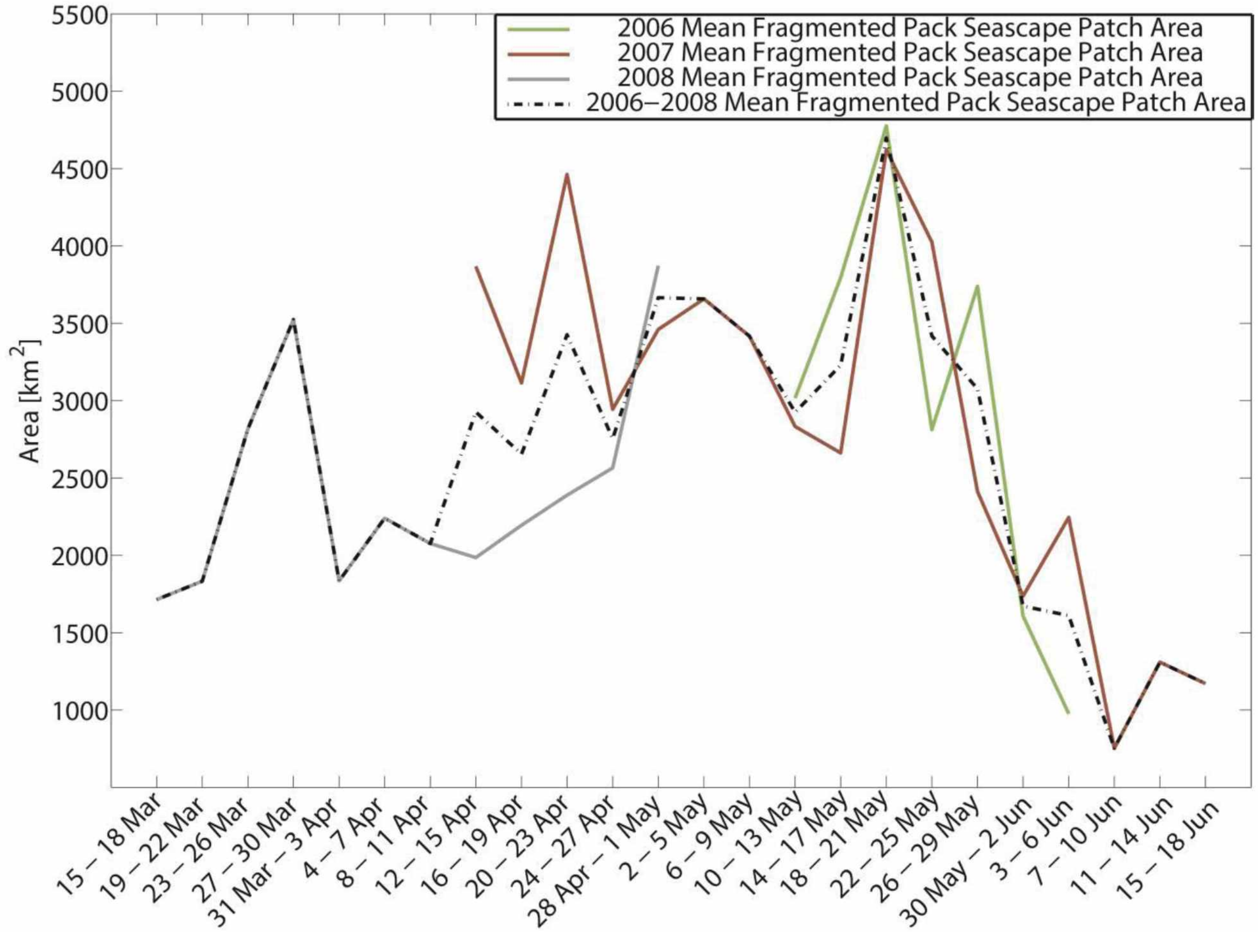

Figure 2.19 Seascape-scale comparison of mean fragmented pack ice-patch area. Mean patch area (black dotted line) and mean fragmented pack ice-patch area from 2006 – 2008 (green, brown, and gray solid lines, respectively) in the Bering Sea. These areas are average area measurements treating each individual patch of fragmented pack as separate.

Relative total fragmented pack ice fraction of the total potential ice area varied considerably for 2006 – 2008 (Figure 2.21). Relative fraction of fragmented pack ice in the Bering Sea ranged from 30 – 50% throughout most of the spring, except for mid-March and early- to mid-June which could indicate the near-maximum of ice extent for winter and ice-free conditions in the Bering Sea, respectively. Total potential ice area decreased at a faster rate than the fragmented pack area, leading to a rapid increase in relative fraction of total fragmented pack near mid-June. Heavy ice conditions in 2008 lead to an early relative fraction minimum of total fragmented pack, leaving the central Bering Sea without persistent coverage (Figure 2.21).

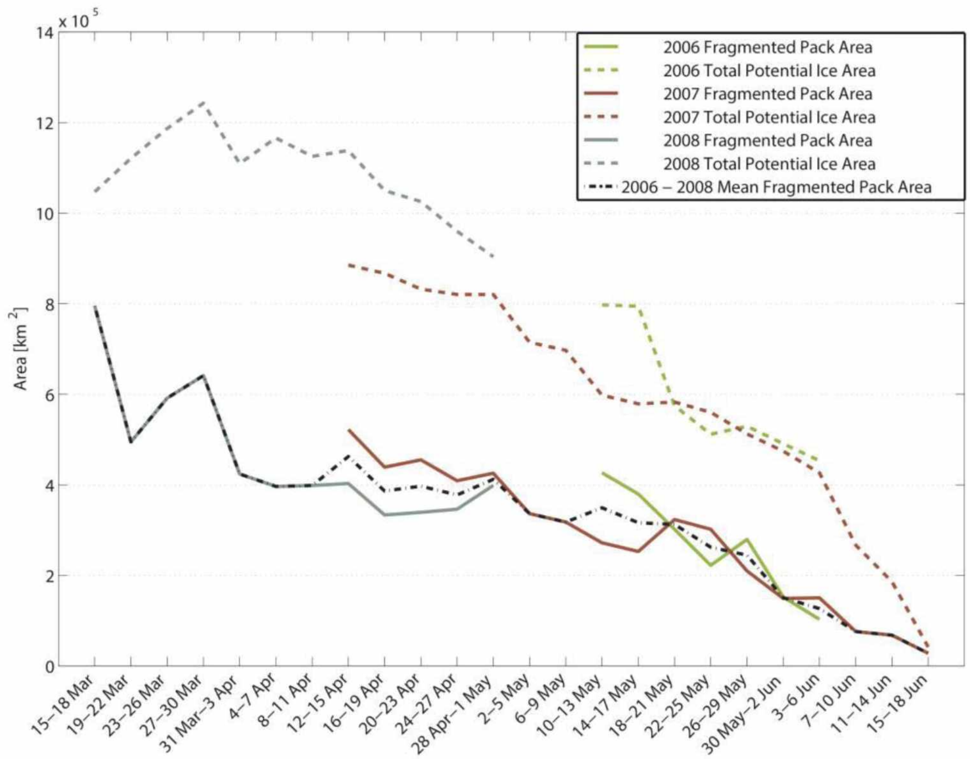

Figure 2.20 Seascape-scale comparison of fragmented pack ice area. Total ice area trends in the Bering Sea are also shown through total potential ice area, calculated from NIC charts.

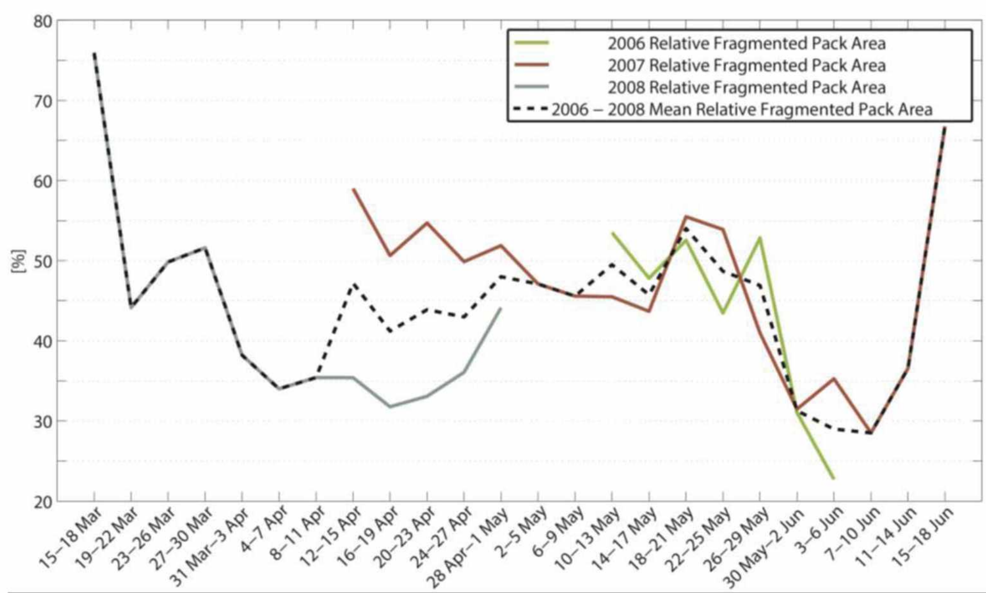

Figure 2.21 The averaged fractional area of the Bering Sea ice cover. This cover is composed of fragmented pack of the combined 2006 – 2008 fragmented pack ice cover.

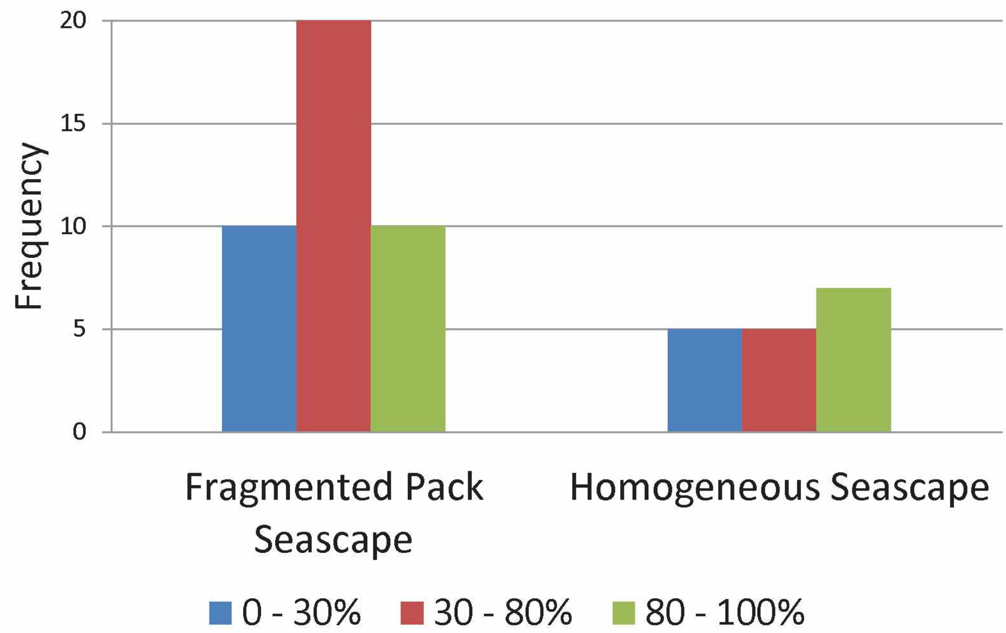

Figure 2.22 SAR classification results compared to ship-based ice observer ice concentrations. Comparisons for years 2006, 2007, and 2008: homogeneous areas consisting of open water or continuous ice pack and fragmented pack ice.

In order to validate our SAR texture-based seascape classifications, we compared 57 ice concentration estimates made by ice observers aboard the 2006 – 2008 Healy cruises (*see* section 2.3.5) that coincided with available SAR data. Of these, 17 ship-based observations corresponded to regions classified as homogeneous texture and 40 to regions of fragmented pack. Seventy percent of ice concentrations within regions of homogeneous SAR texture were observed to be either low (0-3 tenths) or high (8-10 tenths), with five observations of ice concentrations in-between (Figure 2.22). In contrast, ship-based observations corresponding to regions classified as fragmented pack seascapes showed a broader range of ice concentrations with the majority (50%) of observations reporting concentrations in the range 30-80%. These results support the validity of our texture-based approach to seascape classification but suggest there may be some sea conditions in which open water or near continuous ice pack concentrations can resemble fragmented ice. The difference may lie in the scale at which the SAR algorithm is operating, and what a sea-ice observer can perceive from an icebreaker.

2.4.4 Seascape-scale walrus preference for fragmented pack ice

Ship-based observations from 2006 – 2008 identified a total of 8,665 individual walruses (Ray et al. *forthcoming*). The greatest number of walruses was observed in 2006 during the longest of the three cruises, and large herds of walruses were encountered in both 2006 and 2008 (Table 2.9). These walrus observations were grouped in the central and northern Bering Sea, from St. Matthew and the Pribilof islands, north to St. Lawrence Island and the Bering Strait. Ship tracks were limited to the eastern Bering Sea shelf due to the USCGC's restrictions to crossing the international dateline. These ship-tracks also excluded Bristol Bay.

Table 2.9 Statistics for co-located SAR and ship-based observations, 2006 – 2008. These observations were collected within 9.5 hours of available SAR data, and do not reflect the entire ship-based observational dataset.

	No. of observations	Range of observation size of walrus
2006	55	1 – 900
2007	45	1 – 145
2008	32	1 – 450

Georeferenced Shapefiles were created for each SAR image analyzed into seascape classifications. In order to assess whether walruses exhibit a preference for sea ice at the seascape scale, we identified seascape classifications derived from SAR data that were acquired within 9.5 hours of co-located ship-based walrus sightings. This time period represents the shortest time we can expect for ice floes to travel across half the width of a classification window (5km), based on a manual analysis of the drift of recognizable floes in the SAR imagery, which showed that ice floes could drift at speeds up to 14 cm s^{-1}. This is somewhat faster than the modelled ice velocities in the region (Li et al. 2014) but it is within the range of surface currents measured near St Lawrence Island (Danielson et al. 2006) and is therefore useful as a conservative value for our purposes. At this speed, it would take approximately 9.5 hours (570 minutes) for ice to travel half the width of a seascape classification window (5km) and therefore occupy a neighboring classification window rather than the classification window corresponding to the walrus sighting.

Table 2.10 Comparison of SAR seascape classification algorithm to ship-based walrus observations. Data includes those points disqualified by observational time difference from SAR of 9.5 hours. There were 14 matching SAR scenes for each year 2006 – 2008[1].

	2006	2007	2008	Overall
Walruses in fragmented pack	67%	89%	50%	69%
Percentage of fragmented pack ice classifications in walrus-occupied SAR	46%	45%	41%	44%
Walruses in homogeneous textures	32%	11%	50%	31%
Percentage of homogeneous texture classifications in walrus-occupied SAR	54%	55%	59%	56%

[1]Percent of total observations are shown for fragmented pack ice and homogeneous textures of the Bering Sea for each walrus observation obtained for 2006, 2007, and 2008 Healy cruises. Percent for classified areas were calculated from total number of fragmented pack ice and homogeneous texture areas.

By matching ship-observations with SAR data, we were able to identify 132 coincident observations of walruses and SAR-derived seascape between 2006 and 2008 (Table 2.10). With many of these observations made close together in time, this corresponded to 42 different walrus-occupied SAR images, divided between the three years. In each year, the majority of these walrus sightings (~ 69 %) were in regions of fragmented pack (Table 2.10). By comparison, fragmented pack consistently made up less than 50% of the ice-covered areas of walrus-occupied SAR. This suggests that walruses were preferentially occupying fragmented pack.

For those cases where walruses were sighted in areas classified as homogeneously textured ice and ocean, we manually examined the SAR imagery to determine whether it was open water or non-fragmented pack. In most cases, these walruses were located in regions of wind-roughened open water. All sightings in non-fragmented pack were made before mid-May and they were typically located close to identifiable openings. In homogeneous-classified ice and ocean areas derived from SAR data, 91% of the walruses sighted were in groups of 10 or less. The remaining 9% of individuals were in three groups of 20, 40, and 100. Manual inspection of the SAR imagery revealed that the groups of 20 and 100, which were both observed in 2006, occupied regions of open water, while the group of 40, observed in 2008, was in a region of continuous pack ice. In the cases where walruses were observed in areas classified as fragmented pack, 81% of individuals were in groups of 10 or less.

This is a quantitative result that shows walruses do prefer fragmented pack areas of the Bering Sea ice cover. While our classification algorithm segments SAR into only two seascapes compared to Ray, Overland and Hufford's (2010) seascape definition, our method provides a stepping stone to more detailed analyses into walrus, and other marine mammal, use of seascape structures at this scale.

2.5 Discussion

Sea ice in the eastern Bering Sea shelf shows regional variability of patch-scale morphological properties during the spring melt season. Sea ice in the northern zone has the least amount of open water and the greatest amount of young ice, presumably due to higher ice growth rates at higher latitudes. Floes in the northern region are also found in higher densities per km^2 than the southern and central regions. The southern zone, consisting of Bristol Bay and the Pribilof Islands area, exhibits rounder and convex floes, floes smaller in size, and a low young ice concentration and larger open water and thick, first-year sea ice concentration.

For some descriptors (floe density, floe roundness, first-year ice concentration, and open water concentration), the ice patches examined in the southern zone show greater variability than other zones. Some descriptors in Bristol Bay (first-year ice concentration, roundness, convexity, and floe density) show similarities to the central or northern zones with respect to the histogram means and distributions. Since walruses are known to concentrate near St. Lawrence Island and near Bristol Bay, these similarities with the northern zone may provide clues as to what sea ice in Bristol Bay offers to walruses that occupy that area during the winter and spring months.

Comparing occupied and unoccupied ice patches, we found statistically significant differences in floe density, young and open water concentration, and floe convexity, suggesting that walruses were occupying ice patches with floe shape and arrangement atypical to spring

2012 Bering Sea ice patches. Ice patches occupied by adults with YOY were not associated with a specific ice parameter range and thus were not significantly different from unoccupied ice patches, though such YOY-occupied ice patches had the largest floes, on average. These large floe sizes can be explained due to the small sample size of YOY-occupied ice patches, which were less than 10% of the total images occupied by walruses. All other descriptors were similar to unoccupied ice patches, suggesting that walrus adults with YOY examined in this study do not exhibit a preference for specific ice characteristics when choosing where to haul out. Overall, walrus-occupied, with and without YOY, ice patches can be described as follows: first-year ice has a mean concentration of 37% (range 0 – 77%), while young, thin ice concentration averages 30% (range 2 – 74%) and open water covers about 33% (range 4 – 92%) of the surrounding surface. Typically, walruses prefer to haul out or occupy the ocean near floes with a mean floe area of 79 m^2 (range 12 – 804 m^2) and a highly convex shape (mean 0.72, range 0.43 – 0.93), as well as less-rounded floes (mean 0.21, 0.03 – 0.58). Occupied ice patches were typically less-compact, with respect to floe density (mean 308 km^{-2}, range 0 – 1,120 km^{-2}), when compared with unoccupied ice patches. Contrasting our results with that of previous work on ice use by walrus, we see that our analyses of walrus preference of ice (first-year and young ice types) concentration mean of 69% (range 50 – 89%) is near Simpkins et al.'s (2003) observation of high (> 80%) ice concentration preference. Simpkins also specified that walruses tended to occupy areas with large floes (> 48 m). While our data suggests a smaller mean floe diameter (mean 7.6 m, range 4 – 31 m), this floe size is constrained by the ground plane coverage of the aerial images themselves. It is highly unlikely to find floes that large completely contained in these images (Figure 2.4). Evidence of walrus preference for specific sub-regional ice-patch area was not found in the sub-regional analysis using ANOVA and the post-hoc test. This may be due to the limited spatial footprint of the imagery available, which restricts the measurement of floes larger than image ground coverage. While walrus-occupied ice patches displayed some differences from unoccupied patches that could suggest walrus preference at this scale, dependence on fragmented pack ice seascapes by walruses at the seascape scale is more definitive.

Our finding that the majority average (69%) of ship-based walrus sightings in the Bering Sea during the period 2006 – 2008 were in fragmented pack, even though this seascape made up 44%

ice cover, on average, suggests that walruses prefer use of fragmented pack ice seascapes during their spring migration in the Bering Sea. When walruses were not in fragmented pack (31%), they occupied either open water seascapes (17%) or non-fragmented pack ice seascapes (14% of the time). When they occupied non-fragmented pack seascapes, walruses were near visible open water or a lead in the ice 3% of the time, at this scale (see 2.4.4).

Total fragmented pack ice area throughout the spring season showed large variability from year to year. Fragmented pack ice in 2006 was present along the eastern Bering Sea shelf from Norton Sound south past Nunivak Island through most of May, becoming light and melting out into late May, early June. These final days of May display minimal fragmented pack cover northwest of Nunivak Island, west and northwest of St. Lawrence Island, in the Gulf of Anadyr and near St. Matthew Island. Bering Sea ice in 2007 was relatively fractured at the mesoscale, retreating rapidly in late April and early May. This lead to a high relative percentage of fragmented pack cover in mid-April and again in mid-May (both around 55%) before rapid melt and retreat into June, with large areas of open water from early May onward. Relative fragmented pack area in 2008 was 8 – 20% less than in 2007 for matching 4-day periods, which may have contributed to a lower percentage of walruses occupying fragmented pack. In 2008, fragmented pack ice was largely absent southwest of St. Lawrence Island and in the central Bering Sea shelf, and thus could have forced walruses beginning their migration to haul out in areas not typically occupied. Since 2008 was a heavy ice year, with ice extent reaching beyond the climatological extent mean (Ray et al. *forthcoming*), the reduction in fragmented pack area could be due to an increase in continuous pack ice at this scale. Homogeneously textured areas, such as continuous pack ice and open water, could still provide walruses with access to open water or available floes, respectively, but were not picked up by the SAR algorithm. These distinct ice conditions could explain the reason for the large range of walrus sightings that were matched with fragmented pack seascapes. The largest in 2007 when transition from the warm to cold period caused the ice to spread further south and melt rapidly into the spring (Ray et al. *forthcoming*).

The fragmented pack ice, a combination of *broken pack*, *loose pack*, and *pack ice with leads* seascapes identified by Ray, Overland and Hufford (2010), agrees with walrus preference for access to open water or scattered, small to large, or possibly vast angular floes or polynyas. However, currently we are unable to quantitatively identify areas that walruses may potentially avoid throughout the spring due to the lack of persistence of specific seascapes on time scales relevant to walrus. Areas of very-high ice concentration, extreme ice thickness, and lack of access to open water are avoided by walruses, but these properties have not been measured here. The same holds for identification of regions that are impenetrable to walrus, including rounded pack ice seascapes (Ray, Overland and Hufford 2010; Ray et al. *forthcoming*). Identifying such regions is important in the context of management and policy decisions, and population assessments including estimates of recent changes (Ray, Overland and Hufford 2010). While ocean and ice seascapes with homogeneous texture correspond to areas mostly avoided by walrus, a more discriminating classification system to delineate the numerous seascapes present in the Bering Sea during spring melt is needed to increase accuracy and describe qualities of the seascape essential to walrus.

When examining ice-patch descriptors and seascape properties, consideration of scale plays a major part in transferring one measure of habitat properties to another at a separate scale. Since data resolution is an important factor in how objects are perceived in image analysis, certain properties at a finer scale will not show up in a coarse scale. Open water and sea ice concentration, when scaled-up, are properties that help define seascape preference, as would floe-size descriptors. A more robust classification system may take into account surface roughness, especially in evaluating the location of rounded pack ice, distinguishing between broken pack, loose pack, and pack ice with leads (Ray, Overland and Hufford 2010; Ray et al. *forthcoming*), and ice-patch descriptors. Surface roughness features, such as ridge sails, would show increased radar backscatter and thus increase the heterogeneity of the seascape texture, possibly leading to a distinct texture signature. However, not all ice-patch descriptors would have a similar importance at a larger scale.

Both the patch scale and seascape scale analysis must be examined critically, however, for sampling bias and data limitations. At the patch scale, we acknowledge a number of ways in which the airborne sampling approach could introduce bias into our measurements of patch-scale ice descriptors. Flight coverage of the Bering Sea was discontinuous, with 10 days missed due to weather at the beginning of April and May, and near the middle of May. In the early and later stages of the survey, Aero and Otter planes were not flown simultaneously. This lack of temporal coverage during the survey and planes grounded by weather might correspond to periods of anomalous walrus behavior associated with a storm and its aftermath. Walruses might choose floes different from those selected as haul-out sites in calm weather conditions. Ice patches may also be mixed and comprise combinations of floe size, shape, or arrangement different from typical conditions. The ice that walruses would normally prefer may have been pushed in a direction inconvenient for the walruses to follow, leaving them to seek out other ice patches. Additionally, the aerial photographs lacked overlap both along- and across-track, which greatly reduces the maximum floe size considered in our analysis, such that the maximum floe diameter scale is restricted by the image size rather than by the geomorphometrics of floes within a given ice patch occupied by walruses. With four out of the five cameras at mid- to high-oblique angles (12.5° for Aero cameras, 25° for Otter port and starboard cameras), this distorted floe size, shape, concentrations and ground coverage, as well as pixel size. Walrus observations were also biased against walruses that were not near the sea surface or on an ice floe at the time of fly-over. Some ice patches labeled as unoccupied may have been occupied by walruses, which can affect the differences between ice-patch descriptors.

While the seascape analysis exhibited data with ample ground coverage, and overlap, improvements to our methods are suggested. Our seascape classification algorithm ground truth was examined in relation to ship-based observations of ice conditions. Ship-based ice observer concentration records, compared with the SAR algorithm's classification of seascapes, show that the algorithm for distinguishing these two seascapes using texture analysis was successful. In comparison between these observation classification pairings, we must take into account the fact that the classifications are on the spatial scale of 100 km^2 while the observations are on the scale of < 10 km^2, and thus may differ due to scaling the field of view of the observer with respect to the resolution of the subsequent SAR image. In addition to improving ground truth for seascape classification, our data potentially contained measurement errors.

2.6 Conclusions

This study provides a quantitative analysis of the sea ice descriptors and seascape habitat that may be preferential to walruses during their spring migration, mating, birthing, and calf-rearing life cycle events. Walruses seem to prefer, on average, an equal amount of thick, first-year sea ice (37%), thin, young sea ice (30%), and open water access (33%) at the ice-patch scale (< 4 km^2). Floes are relatively larger (79 m^2) than typical floe area of unoccupied ice patches. Convex (0.72) and relatively rounded (0.21) floe shapes are typical of walrus-occupied ice patches. Floe density (308 km^{-2}) remains lower in walrus-occupied ice patches than unoccupied ones, providing open water and may provide a larger distance between floes.

Walruses also are shown to prefer a fragmented pack ice seascape, which has characteristics corresponding to seascapes of broken pack, loose pack, and pack ice with leads as defined by Ray, Overland and Hufford (2010). Walruses were observed in fragmented pack ice seascapes 69% of the time, on average, between 2006 and 2008. During this time period, total fragmented pack seascape area covered an average of 44% of the total potential ice cover in the Bering Sea. This seascape is beneficial to walruses during their spring migration by providing continuous access to open water leads and a divergently-moving ice pack. The fragmented pack ice seascape is constantly evolving throughout the spring melt period as well, typically highly concentrated near land boundaries and the edge of the ice-water boundary at the southern end of the Bering Sea shelf. The relative fraction of total fragmented pack ice area during 2006 – 2008, in relation to total potential ice area, shows, on average, a steady trend of 30 – 50% throughout April and May. High relative fraction (> 60%) of total fragmented pack area occurs near the ice extent maximum and during the final days of ice presence in the Bering Sea.

Future studies should consider a variety of spatial scales between 4 m^2 and 9,000 km^2 beyond what were studied here. Optimal biologically-relevant scales that encompass natural history and sea-ice dynamics during and after the period in which distinct seascapes are present in the Bering Sea are important to describing not only preference, but whether *adaptation* may occur, if completed across longer time scales. Behavioral studies of walruses during the changing ice cover may provide evidence of adaptation and are also needed to assess how walruses interact with ice patches and seascapes beyond presence-absence analyses. Analysis of sea ice throughout the entire winter-spring season, from December through June for each year, would provide a complete view of changing ice conditions. Aerial imagery that has greater ground coverage, similar resolution and coincides temporally and spatially with other data that exhibit larger coverage areas in the Bering Sea will assist in determining this optical scale. Our findings are dependent on data scale, coverage, and resolution, which may suggest different preferences if further analysis with a wider array of data products is completed. In addition, more sophisticated image analysis techniques, such as wavelet analysis to distinguish ice from ocean, would allow for a more complete picture of the seascape cover. Further investigation and delineation of various seascapes outside the two studied here will allow classifications to diminish seascapes that would not be occupied by walrus, such as loose- and rounded-pack seascapes. Finally, intensive study of the Bering Sea ice would assist in describing how the sea ice evolves with any walrus preferences found.

We have shown that walruses may prefer certain ice conditions at multiple spatial scales, and that these ice conditions are highly dynamic and variable throughout the season. Whether these conditions continue to persist, or whether walruses will have to adapt to a new regime of ice-patch and seascape types remains to be seen. Walrus occupation of certain ice-patch descriptors and seascapes are important from a management perspective. Measurable, quantitative methods to equate sea-ice types with walrus occupation can assist in investigating how walruses may adapt to changing ice conditions using available SAR and aerial data to assess past and present ice use. Further study of sea ice in the Bering Sea and modeling of potential future conditions can also provide the tools for proactive management aimed at mitigating negative impacts of climate change and loss of sea-ice habitat, important for foraging, migration, rearing of young, and a host of other life-cycle events. Anticipating further reduction in sea ice preferable to walrus, shipping, energy, and tourism pursuits, which should increase with the opening of the Northwest Passage and further decrease in summer sea-ice extent, boundaries and marine protected areas could be created while walruses recover or adapt.

2.7 Acknowledgements

This research is supported by National Science Foundation award #1125040, CDI-Type I: Collaborative Research: A Computational Thinking Approach to Mapping Critical Marine Mammal Habitat Through Readily-Deployable Video Systems. Aerial images presented in this study were collected through the 2012 NOAA Bering-Okhotsk Seal Survey (BOSS). The NOAA BOSS program collected images under the National Marine Fisheries Service (NMFS) Marine Mammal Protection Act (MMPA) Permit #15126, in order to be in close proximity to marine mammals during flights. I gratefully thank the scientists, pilots, and all who assisted in the 2012 NOAA BOSS program, especially Kym Yano and Michael Cameron for providing support for this research. I also gratefully acknowledge the Alaska Satellite Facility for providing Canadian Space Agency's Radarsat-1 data (with Scott Arko and Dr. Rudi Gens providing support), and the captain, crew, and scientists on USCG Healy cruises for 2006 – 2008.

2.8 References

Berta, Annalisa, James L. Sumich, and Kit M. Kovacs. 2006. “Energetics.” In Marine Mammals: Evolutionary Biology, edited by Annalisa Berta, James L. Sumich, and Kit M. Kovacs, 2nd ed., 213–36. Amsterdam: Elsevier. doi:http://dx.doi.org/10.1016/B978-012088552-7/50010-2.

Braham, Howard W, J.J. Burns, G.A. Fedoseev, and B.D. Krogman. 1984. “Habitat Partitioning by Ice-Associated Pinnipeds: Distribution and Density of Seals and Walruses in the Bering Sea, April 1976.” In Soviet-American Cooperative Research on Marine Mammals . Volume 1- Pinnipeds, edited by Francis H. Fay and Gennadii A. Fedoseev, 25–47. NOAA.

Brown, Zachary W., and Kevin R. Arrigo. 2012. “Contrasting Trends in Sea Ice and Primary Production in the Bering Sea and Arctic Ocean.” ICES Journal of Marine Science: Journal Du Conseil 69 (7): 1180–93. doi:10.1093/icesjms/fss113.

Burn, Douglas M., Marc A. Webber, and Mark S. Udevitz. 2006. “Application of Airborne Thermal Imagery to Surveys of Pacific Walrus.” Wildlife Society Bulletin 34 (1). Blackwell Publishing Ltd: 51–58. doi:10.2193/0091-7648(2006)34[51:AOATIT]2.0.CO;2.

Burns, John J., Lewis H. Shapiro, and Francis H. Fay. 1980. “Ice as Marine Mammal Habitat in the Bering Sea.” In The Eastern Bering Sea Shelf: Oceanography and Resources, edited by D.W. Hood and J.A. Calder, 781–97. Fairbanks: University of Alaska Press.

Canadian Space Agency. 2013. “Radarsat-1 Data 2004 - 2008.” Alaska Satellite Facility. Accessed March 31. http://www.asf.alaska.edu.

Cavalieri, D.J., and C.L. Parkinson. 2012. “Arctic Sea Ice Variability and Trends, 1979-2010.” The Cryosphere 6 (4). Copernicus Publications: 881–89. doi:10.5194/tc-6-881-2012.

Danielson, S., K. Aagaard, T. Weingartner, S. Martin, P. Winsor, G. Gawarkiewicz, and D. Quadfasel. 2006. “The St. Lawrence Polynya and the Bering Shelf Circulation: New Observations and a Model Comparison.” Journal of Geophysical Research: Oceans 111 (C9): C09023. doi:10.1029/2005JC003268.

Fay, F.H. 1982. “Ecology and Biology of the Pacific Walrus, Odobenus Rosmarus Divergens Illiger.” North American Fauna, 1–279. http://www.fwspubs.org/doi/abs/10.3996/nafa.74.0001.

Fish and Wildlife Service. 2007. “Record Sea Ice Retreat: Walrus Conservation and Management Issues in the Chukchi Sea.” http://alaska.fws.gov/fisheries/mmm/walrus/pdf/walrus_conservation_issues_chukchi.pdf.

Haralick, R.M., K. Shanmugam, and Its’Hak Dinstein. 1973. “Textural Features for Image Classification.” Systems, Man and Cybernetics, IEEE Transactions on. doi:10.1109/TSMC.1973.4309314.

Jay, Chadwick V., and Anthony S. Fischbach. 2012. “Walrus Areas of Use in the Chukchi Sea during Sparse Sea Ice Cover.” Marine Ecology Progress Series 468: 1–13. http://www.int-res.com/abstracts/meps/v468/p1-13/.

Jay, Chadwick V., Mark S. Udevitz, Ron Kwok, Anthony S. Fischbach, and David C. Douglas. 2010. “Divergent Movements of Walrus and Sea Ice in the Northern Bering Sea.” Marine Ecology Progress Series 407: 293–302. doi:10.3354/meps08575.

Kapsch, Marie-Luise, Hajo Eicken, and Martin Robards. 2010. “Sea Ice Distribution and Ice Use by Indigenous Walrus Hunters on St. Lawrence Island, Alaska.” In SIKU: Knowing Our Ice, edited by Igor Krupnik, Claudio Aporta, Shari Gearheard, Gita J. Laidler, and Lene Kielsen Holm, 115–44. Springer Netherlands. doi:10.1007/978-90-481-8587-0_5.

Krupnik, Igor, and G. Carleton Ray. 2007. “Pacific Walruses, Indigenous Hunters, and Climate Change: Bridging Scientific and Indigenous Knowledge.” Deep Sea Research Part II: Topical Studies in Oceanography 54 (23–26): 2946–57. doi:http://dx.doi.org/10.1016/j.dsr2.2007.08.011.

Kwok, R., and G.F. Cunningham. 2015. “Variability of Arctic Sea Ice Thickness and Volume from CryoSat-2.” Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 373 (2045). http://rsta.royalsocietypublishing.org/content/373/2045/20140157.abstract.

Li, Harbin, and Jianguo Wu. 2004. “Use and Misuse of Landscape Indices.” Landscape Ecology 19 (4). Kluwer Academic Publishers: 389–99. doi:10.1023/B:LAND.0000030441.15628.d6.

Li, Linghan, Arthur J. Miller, JulieL. McClean, Ian Eisenman, and MyrlC. Hendershott. 2014. “Processes Driving Sea Ice Variability in the Bering Sea in an Eddying Ocean/sea Ice Model: Anomalies from the Mean Seasonal Cycle.” Ocean Dynamics 64 (12). Springer Berlin Heidelberg: 1693–1717. doi:10.1007/s10236-014-0769-7.

Lu, P., Z.J. Li, Z.H. Zhang, and X.L. Dong. 2008. “Aerial Observations of Floe Size Distribution in the Marginal Ice Zone of Summer Prydz Bay.” Journal of Geophysical Research: Oceans 113 (C2): C02011. doi:10.1029/2006JC003965.

“MATLAB and Image Processing Toolbox.” 2012. Natick: The MathWorks, Inc. http://www.mathworks.com/products/matlab/.

Mcnutt, S. Lyn, and James E. Overland. 2003. “Spatial Hierarchy in Arctic Sea Ice Dynamics.” Tellus A 55 (2). Munksgaard International Publishers: 181–91. doi:10.1034/j.1600-0870.2003.00012.x.

National Ice Center. 2006. “Compiled by F. Fetterer and C. Fowler.” Boulder, Colorado USA: National Ice Center Arctic sea ice charts and climatologies in gridded format. doi:http://dx.doi.org/10.7265/N5X34VDB.

Otsu, Nobuyuki. 1979. “A Threshold Selection Method from Gray-Level Histograms.” IEEE Transactions on Systems, Man, and Cybernetics 9 (1): 62–66. doi:10.1109/TSMC.1979.4310076.

Overland, James E., and Muyin Wang. 2013. “When Will the Summer Arctic Be Nearly Sea Ice Free?” Geophysical Research Letters 40 (10): 2097–2101. doi:10.1002/grl.50316.

Pease, Carol H. 1980. “Eastern Bering Sea Ice Processes.” Monthly Weather Review. doi:10.1175/1520-0493(1980)108<2015:EBSIP>2.0.CO;2.

Pittman, Simon J., Ronald T. Kneib, and Charles A. Simenstad. 2011. “Practicing Coastal Seascape Ecology.” Marine Ecology Progress Series 427: 187–90. http://www.int-res.com/abstracts/meps/v427/p187-190/.

Ray, G.C., and G.L. Hufford. 1989. “Relationships among Beringian Marine Mammals and Sea Ice.” Rapports et Procès-Verbaux Des Réunions Conseil International Pour l’Exploration de La Mer 188: 225–42.

Ray, G. Carleton, James E. Overland, and Gary L. Hufford. 2010. “Seascape as an Organizing Principle for Evaluating Walrus and Seal Sea-Ice Habitat in Beringia.” Geophysical Research Letters 37 (20): n/a – n/a. doi:10.1029/2010GL044452.

Ray, G. Carleton, Gary L. Hufford, James E. Overland, Igor Krupnik, Jerry McCormick-Ray, Karen Frey, and Elizabeth Labunski. Forthcoming. “Decadal Bering Sea Seascape Change : Consequences for Pacific Walruses and Indigenous Hunters.” Ecological Applications. doi:http://dx.doi.org/10.1890/15-0430.1.

Ray, G. Carleton, and D. Wartzok. 1974. “BESMEX: Bering Sea Marine Mammal Experiment.” Moffett Field, 56. http://hdl.handle.net/2060/19750005431.

Shokr, Mohammed E. 1991. “Evaluation of Second-Order Texture Parameters for Sea Ice Classification from Radar Images.” Journal of Geophysical Research: Oceans 96 (C6): 10625–40. doi:10.1029/91JC00693.

Simpkins, Michael A., Lisa M. Hiruki-Raring, Gay Sheffield, Jacqueline M. Grebmeier, and John L. Bengtson. 2003. “Habitat Selection by Ice-Associated Pinnipeds near St. Lawrence Island, Alaska in March 2001.” Polar Biology 26 (9). Springer-Verlag: 577–86. doi:10.1007/s00300-003-0527-7.

Soh, L.-K., and C. Tsatsoulis. 1999. “Texture Analysis of SAR Sea Ice Imagery Using Gray Level Co-Occurrence Matrices.” Geoscience and Remote Sensing, IEEE Transactions on. doi:10.1109/36.752194.

Wedding, Lisa M., Christopher A. Lepczyk, Simon J. Pittman, Alan M. Friedlander, and Stacy Jorgensen. 2011. “Quantifying Seascape Structure: Extending Terrestrial Spatial Pattern Metrics to the Marine Realm.” Marine Ecology Progress Series 427: 219–32. http://www.int-res.com/abstracts/meps/v427/p219-232/.

Wendler, G., L. Chen, and B. Moore. 2013. “Recent Sea Ice Increase and Temperature Decrease in the Bering Sea Area, Alaska.” Theoretical and Applied Climatology 117 (3-4). Springer Vienna: 393–98. doi:10.1007/s00704-013-1014-x.

World Meteorological Organization. 2014. “WMO Sea-Ice Nomenclature.”

Wu, Jianguo, and R.J. Hobbs. 2007. “Landscape Ecology: The State-of-the-Science.” In Key Topics in Landscape Ecology, 271–87.

3 Traditional ecological knowledge of sea ice and walrus ice-patch preference near St. Lawrence Island[2]

3.1 Abstract

Alaskan native subsistence communities in the Bering Sea utilize sea ice for hunting marine mammals, such as the Pacific walrus, during the winter and spring-melt season. Two communities that rely on walruses include Gambell and Savoonga, located on St. Lawrence Island. Semi-directed interviews were conducted with one elder in Savoonga, as well as two elders and two middle-aged hunters in Gambell. Informants were provided aerial photographs of walruses on sea ice near St. Lawrence Island and a place map of the northern Bering Sea region to stimulate discussion. Through these interviews, knowledge of walrus-ice associations, walrus behavior during the spring migration, and the changing ice and climate conditions were discussed. Recent sea-ice decline has caused changes in the types of floes that walruses typically encounter. Walruses were observed, historically and in recent times, to prefer floes with large ice ridges in order to hide from predators and shield themselves from harsh weather. Availability of open water and sufficient ice thickness were also noted as important. Overall, changes in the reliability of sea ice that subsistence crews utilize for the harvest, along with recent sea-ice decline and thinning of the pack ice, have contributed to an inconsistent walrus harvest in recent years. Climate change is blamed for the changing sea-ice, weather, and ocean environment that were not previously observed in historical records passed down through time. These include an increase in the occurrence of strong storms, loss of shorefast sea ice around St. Lawrence Island, and a thinner, less stable ice cover during the harvest season. In describing sea-ice characteristics, or ice-patch descriptors (size, shape, and arrangement of floes in an ice patch), quantitatively through aerial imagery at a spatial scale of less than 4 km^2, comparison with these traditional ecological knowledge observations is examined. These potentially important ice-patch descriptors typically did not translate to the traditional knowledge perspective. Floe shape was not recognized as an important ice feature, nor was it important for hunting use. Floe-size

---

[2] Sacco, A.E. and Eicken, H., Traditional ecological knowledge of sea ice and walrus ice-patch preference near St. Lawrence Island, publication forthcoming.

preference was generally described as being critical to smaller floes. Open water availability was described as important, either between floes or by access through thin young ice. Perspective is the main distinction between our quantitative sea-ice descriptor results, using remote sensing techniques, and traditional knowledge. Remotely-sensed ice-patch descriptors are a static measurement, while traditional knowledge views ice properties in the context of constantly changing landscapes using indicators, proxies, and mismatches to describe the changing Arctic.

3.2 Introduction

The purpose of this paper is to explore and compare various scientific data presented in the previous chapter (2) on walrus use of sea ice and to discuss these data in the context of traditional ecological knowledge (TEK). TEK is defined as the ecological knowledge that stems from extensive observation of an area and species (Huntington 2000). Through this study, we show that TEK plays an important role in a species' habitat analysis, definition, and preference. The knowledge of Alaska Native subsistence hunters, who harvest walruses and other marine mammals for their livelihood, are especially important to any management decision that may be decided on when the U.S. federal government determines whether the Pacific walrus' changing habitat warrants listing with under the Endangered Species Act (ESA) in 2017.

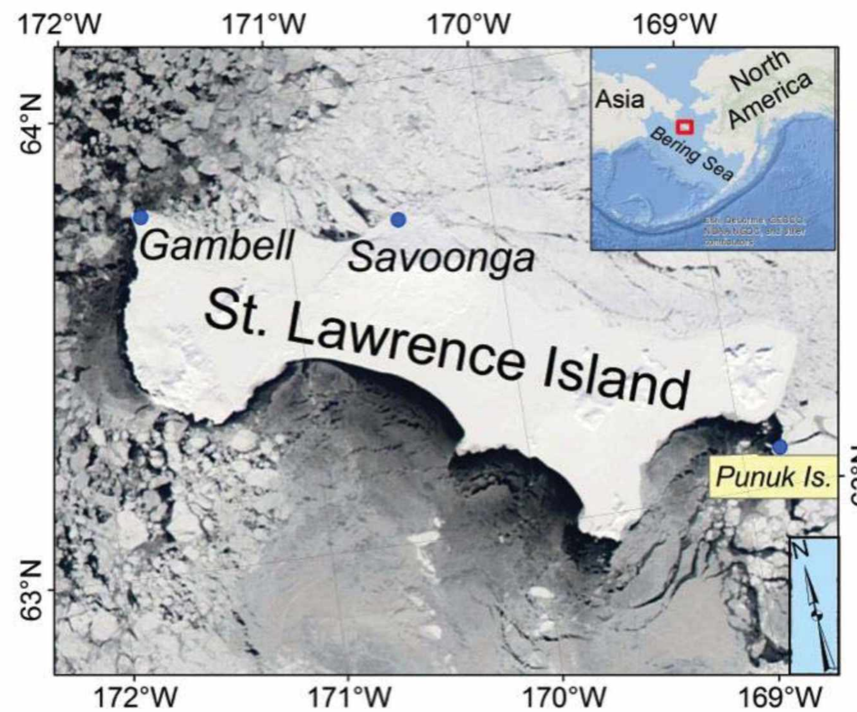

Figure 3.1 Map showing St. Lawrence Island. This map includes the two Alaskan Native villages, Gambell and Savoonga, as well as the Punuk Islands, which are frequently used by walruses. These lie in the Bering Sea, between North America and Asia. The background scene is a MODIS Aqua image from March 15, 2015, during the second visit by the author to the island (Vermote et al. 2015).

For millennia, indigenous communities bordering the Bering Sea, in both what is currently Alaska and Chukotka, have relied on a subsistence lifestyle harvesting marine mammals, including walruses (Krupnik and Ray 2007). TEK can encompass recent and historical observations as well as knowledge passed down through many generations. In ecology, TEK can supplement resource management policy, impact assessments, and other ecological research (Huntington 2000). Unfortunately, TEK's utility is not fully established in the scientific community. TEK may be challenged and disregarded as imprecise from a scientific point of view, since integration with scientific methods used by researchers is difficult to implement. Within the sea-ice system framework, however, TEK observations of sea-ice system characteristics, from animals to climate processes, hazards, and threats, provide a comprehensive, broader worldview of the Arctic climate system (Eicken 2010).

Currently, the Eskimo Walrus Commission represents 19 walrus hunting communities in western Alaska in resource co-management and self-regulation issues. Two of these communities, Savoonga and Gambell, both on St. Lawrence Island, depend on Pacific walrus hunts in order to thrive (Figure 3.1) (Krupnik and Ray 2007; Robards, Kitaysky, and Burns 2013). The Pacific walrus overwinters in the Bering Sea, mainly in Bristol Bay and near St. Lawrence Island. Walruses use sea ice as a moving central-place foraging platform, a resting surface, as an arena for mating rituals, and a place to raise their young and avoid predators (Fay 1982; Fay, Ray and Kibal'chich 1984; Ray et al. 2006; Krupnik and Ray 2007). Near St. Lawrence Island, walruses have access to food (Ray et al. 2006), a broken pack seascape on which to haul out on and have continual access to water (Ray, Overland and Hufford 2010), and areas in which to mate (Fay, Ray and Kibal'chich 1984).

In the previous chapter, we found that walrus groups show potential preference for particular sea ice descriptors at the ice-patch scale (< 4 km^2). Descriptors were divided into three classes: size of floes, shapes of floes, and the arrangement of the ice patch. Walruses were shown to prefer ice patches with larger floes (as measured by area, perimeter, and diameter) than those typical of the Bering Sea during the spring melt season. They were also shown to occupy ice patches that contained floes with higher convexity and roundedness and fewer floes per unit area than unoccupied ice patches. Less young sea-ice cover and more open water concentration were also shown to be typical of walrus-occupied ice patches. We compare these results, which are based on remotely-sensed data and observations, along with image analysis techniques, to TEK from elders and walrus hunters in Savoonga and Gambell, based on thousands of years of direct observation.

3.3 Data & methods

The research presented below followed Institutional Review Board (IRB) procedures and was approved by the University of Alaska Fairbanks' IRB Office as Protocol # 662539-2. I completed the required coursework in Social and Behavioral Responsible Conduct of Research (Collaborative IRB Training Initiative Course Completion Record # 14137504) and Social Behavioral Research Investigators and Key Personnel (Collaborative IRB Training Initiative Course Completion Record # 14137503). IRB approval (Appendix 3.A) was sought before the study began, and was granted prior to any interviews that were conducted.

Semi-directed interviews were conducted due to the relaxed nature of the question and answer session for the participant, resembling a typical conversation. In this approach, a general list of questions for the interview are created that can steer the conversation in the study direction, but questions are open-ended and allow the participant to have some leeway in answering the interview questions and freedom to discuss issues that may not have come up in rigid, structured interview (Huntington 2000). All interviews were conducted in English and were conducted during two visits to St. Lawrence Island: (i) February 13 – 18 (Savoonga) and February 18 – 22 (Gambell) and (ii) March 15 – 22 (Gambell).

Between the two trips to St. Lawrence Island, five informants were interviewed, selected by recommendations from fellow scientists, from Savoonga and Gambell, the two Alaskan Native villages on St. Lawrence Island. These villages combined have a population of 1,352 (U.S. Census Bureau 2010 a,b). The informants in the study included one elder from Savoonga and two elders and two hunters from Gambell. Each participant was given a consent form and, if consent was given, an audio recording of the interview was created. Only one participant declined to be recorded. Four of the five informants asked to remain anonymous. The mean age of the informants is estimated to be around 50, since the age of informants was not collected. Recorded interviews were manually transcribed and used throughout the following sections to provide insight into described ice conditions, walrus behaviors, and use of sea ice.

The general list of questions for the semi-directed interviews was the same for each participant. These questions can be found in Appendix 3.B. During the interviews, the informants used or were shown a nautical map of the northern Bering Sea region, including the ocean surrounding St. Lawrence Island and a set of 45 aerial photographs of walrus-occupied sea ice in the Bering Sea. The nautical map was presented to informants during the entire interview for reference and ease of relaying and relating information that the participant was providing. This map was nautical map 96036 from the Defense Mapping Agency Hydrographic /Topographic Center.

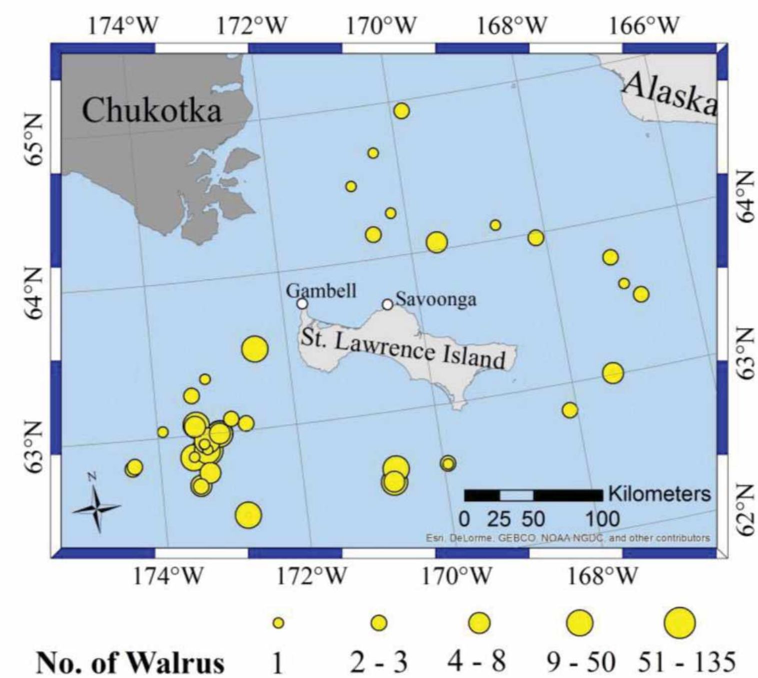

Figure 3.2 Aerial walrus observation locations shown to informants. White dots designate locations of the St. Lawrence Island communities of Gambell and Savoonga and yellow dots represent walrus presence. These images, including only those images which contained walruses hauled out on ice floes, were printed and shown to informants in order to stimulate memories of ice conditions and walrus behavior.

The photographs shown to the informants were a subset of images acquired by the NOAA Bering-Okhotsk Seal Survey (BOSS) program in 2012, showing regions of ice ranging from 3,500 – 4,100 m^2 in area and occupied by one or more walruses. The photographs were printed, bound, and shown to study informants in order to provide a visual reference to ice conditions with walruses present. Locations of these aerial observations were selected to be within 100 miles of the study area (Figure 3.2). Each participant was asked to discuss the ice features or walrus behavior they have seen and to reference as many photos as they wanted. This proved to be quite successful, as each participant enjoyed the visual aspect of seeing walruses with sea ice, which prompted them to relate hunting stories or anecdotes on hunting walruses based on the ice and walrus characteristics in the photograph.

3.4 Local observations of contemporary and historical conditions

Ice conditions during both visits varied substantially. During February, the north coast of Savoonga contained sea ice that was thin, fractured, and slushy. This ice, as described by inhabitants (Informants A in Savoonga, B-D in Gambell, and informal discussions that occurred in both communities), was not suitable or safe for traveling on or through in order to hunt (Figure 3.3). The sea ice in February was similar to brash ice, consisting of a mixture of ice fragments that were less than one meter in thickness. In January, the previous month, ice began to form along the shore, but strong winds precipitated a breakout event that caused the shorefast ice to drift away. This sediment-laden brash ice then closed along the coast of Savoonga and prevented hunters from safely navigating the surrounding ice. Thus, due to the lack of a stable, favorable ice conditions, opportunities were missed for harvest of walruses and other marine mammals. During the first week of February 2015, walruses were spotted passing by Savoonga. Since the ice and weather conditions were poor, boat captains were unable to pursue these walruses. Informant A from Savoonga describes the current conditions in relation to past ice conditions:

> We used to watch within the hour, ice would form on the open water. And the openings and it would be like ice would form within an hour, an inch thick. Within 2 hours, it would be like 2 inches thick. Yeah. Now it's like it's all slushy. Yeah, and kind of a dangerous thing for, you know, young people who never gone

> out hunting. Yeah, they [Gambell residents] got lucky couple months ago; the walruses hauling out only 2-3 miles out, and that was on the shore ice, the new ice that was forming. And after that one week, we had lot of south winds hitting 40, 50 miles an hour. All that area through Gambell and here, ice was all gone. For, you know miles and miles and it was too windy and too rough to go out anyways. And a lot of the factors that I think caused [it]; weather is changing all the time.

However, by the third week of February, walruses were spotted near Southeast Cape off of St. Lawrence Island and hunting teams were hopeful of a successful catch.

Figure 3.3 Sea ice on the north side of Savoonga village. Buildup and thin, slushy ice in the background make for unsafe hunting conditions. Photo taken by Alexander Sacco, February 2015.

The ice in March was more stable, solid, and formed into pack ice with lead features (Figure 3.4). While ice conditions improved for hunting in the 3 weeks between visits to the island, there were still large expanses of open water near the village of Gambell, which is described as a current feature of the near-shore ice conditions by Informant D from Gambell: "In the past…even with just straight north winds, the west side of the beach would be plugged with ice too, uh, it's just not happening this year [2015]. Last year [2014], also was like that. North, northeast winds, a lot of open water, on the west side." Ice fishing had commenced at this time, and seal hunting had begun. Walrus hunts had also begun after the February visit. Usually the ice comes in December, but it did not show up until mid-January in 2015. Informant D from Gambell commented that this year had been the worst ice year they've seen in recent times:

> This here, you know, it's been probably the worst year, with the ice conditions. Usually we do get the ice, maybe; I remember in the past like, early December, but this year I've noticed that uh ice did not get in [un]til like middle of January, late January, which is, you know, more likely than not caused by global warming. The ice now that I've seen is really, really poor. Ever since the ice got in it seems like the ice that just formed from this year.

In the last decade, sea ice has reached the coasts of Gambell and Savoonga as early as October, with initial ice seal hunting commencing in November, and stable, winter-spring shorefast ice forming by late-December which would last until spring (Oozeva et al. 2004). Ice system observations can be described through important proxies such as the freezing of the coastal gravel or the first appearance of slush ice. The timing of ice proxies were also similar in 2006 – 2008 when observations were collected by Krupnik, Apangalook Sr. and Apangalook (2010). From 2006 – 2009, solid winter conditions are not being seen until late December or early January, as ice that is arriving to the area is thin, broken ice that is less stable (Krupnik, Apangalook Sr. and Apangalook 2010).

Concerns are also high that older ice, which can provide a sturdy platform on which to hunt or butcher harvested mammals, is not present anymore. Recent local observations of ice conditions show ice that is sometimes not thick enough to butcher a walrus without fracturing, creating a hazard for hunters and the walruses that occupy floes. Informant A from Savoonga described the challenges of hunting walruses when ice has become too thin:

> Last year when we went out hunting, we got to where we got walrus and we pulled up our boat so we all get on the ice, flat ice, it … looked pretty thick, but it wasn't so we were all there out of the boat pullin' the walrus on the ice. We got it to the middle of the ice, and it was a good thing that most of us were on one side where the boat is and only Pete was on where the other side was. Right where we had pulled up the walrus on the ice that big, big ice broke right in half. I threw a rope towards it and catch so it didn't, you know, fall back in, but we had to take that walrus, tie it back on the boat, go look for another piece of ice to work on; to butcher… but it was like, maybe, good 10-15 minute boat ride [un]til we go to another ice floe.

Figure 3.4 Sea ice near Gambell, Alaska on March 15, 2015. The ice fragments were is coalesced into pack ice with lead features. Photo taken by Alexander Sacco, March 2015.

Shorefast ice has also been untrustworthy in the past few years, as northeast and east winds pushed the shorefast ice away from the coast, causing it to never raft or ridge and attach to the coast. Ice keels that reach the seafloor, grounding them in place, are also not as common in recent times. Ridging was not seen by hunters interviewed in February and March of 2015 and confidence in a good ice year has decreased due to a lack of stable shorefast ice. Typically, hunting parties would travel to the edge of the shorefast ice to launch their boats, but without this ice in place, it is not safe to go hunting. This causes unsafe hunting conditions and hunting parties are often left to wait for better ice, ocean, and wind conditions before attempting departure. In 2014, shore ice was present with southerly winds dominating. However, in 2015, informant D from Gambell noted that the east and northeast winds pushed the ice away from the shore and it was not anchor to the coast:

> Pretty different year than the rest, it's been worse, *worser* than last year [2014]…last year [2014] there was a little bit of shore ice, even a little bit of south winds pick up. There were some shore ice but this year even from northeast or east winds pushed the shore ice on the north side, just doesn't hold on. Usually in the past there was ice, you know, that overlaps each other so much that they hit on the bottom of the water to the land and that would help us form shore ice, you know, on the west side, north side. That I did not see at all this year whatsoever, so, you know it, more likely than not, that the ice is just gonna keep coming off every time north winds hit our [coast], you know, even if it's, even if it's pretty

> calm water there, the [wind] will just take it right out… yeah, that's one thing I didn't see this year. Usually, every year, even last year [2014], there was a little bit, not as much as it was in the past, the ice that overlap each other, so much that it hits the bottom of the water, where it can hold some of the ice.

Informer A from Savoonga believes that the poor ice conditions are caused, in part, by contamination of a slick, oily-type substance that covers the ice and prevents it from freezing together: "It's [oily-type substance] affecting the ice to get thinner and thinner, and I had not seen anything slimy ever before on ice, and now it's like, some kinda slime, some bacterial slime, that keeps the ice like a slush, instead of hard cubical ice that you can freeze it."

The thin ice continued to cover the shoreline due to northerly winds dominating the area, instead of southerly winds, during the winter. Major storms, particularly one in 2014 that reached wind speeds of around 160 knots, were reported to hinder community success in hunting. Some community members acknowledged storms that they've heard about in the eastern United States, where strong winter storms were not common in the past. Described as a cycle, each weather system is connected in the minds of the community members. From low pressure systems traveling north through the Pacific Ocean to Alaska, shifting towards Canada, and then circulating to the contiguous United States, these storms are said to be changing the way the weather behaves. Those that voiced their opinions agree that climate change is the main driver in all environmental changes they are experiencing: ocean currents, ice, weather, and in turn, changes in walrus behavior.

3.5 Observations of walrus behavior during the spring hunt and birthing

When asked about the difference between the Bristol Bay walrus sub-population and those walruses that stay near St. Lawrence Island and the Gulf of Anadyr, informants described these walruses as being visually distinctive, based on size and weight. Differing from standard scientific convention, Informant A from Savoonga referred to walruses from the Bristol Bay area as *Pacific walrus*, and observed them to be much smaller than the average *Bering Sea* walrus, defined as those walruses that typically spend their winters near St. Lawrence Island. Informant A stated that these *Pacific* walruses congregate at Punuk Islands in the summer. The *Bering Sea* walruses are known to travel west to east around the island in April and May, during the time that females start giving birth. Punuk Islands are an important sanctuary for elder walruses, as observed by Informant A:

> [At Punuk Island, walruses] in the haulout will, die off, and it's like a sanctuary. Like where the walruses die off. Walruses tend to take their elders the oldest walruses, when they can't thrive with them anymore and push them towards the shore. They push them towards the shore, hitting them with their tusks, until the walrus can't bother them anymore. When the walrus gets very, very old, they can't seem to be able to, you know, feed with the other walruses. They get skinny and the stronger walrus winds up, you know, taking that advantage of when their frenzying. And older walrus get pushed aside, as they get older. And, what happens is, every four to some years, the old walruses, females and males, will go get pushed to die-off, right here at Punuk Island, sometimes up to 200 walruses will die off on that island.

At the beginning of the walrus' life cycle, we see protection of walrus young-of-year (YOY) is the highest priority. As a female walrus approaches the end of its pregnancy, she will separate herself from her herd to give birth on segregated, small floes. The calving walrus may prefer an area with a lot of ice around (Figure 3.5), but she will occupy the first available floe and abandon the area as soon as the calf is strong enough to leave. She will then take her calf to a different floe away from the blood, which may attract predators. Informant A from Savoonga describes how calving females seek solitude during the birthing process:

> A walrus with its calf, when a walrus goes to have its calf, it takes off from its herd, so then she's all by herself. Especially with the two-year old, 3-year old walrus, and she's mature enough to have a calf, she'll take off from the herd and have her calf alone…the mother walrus will tend to wanna be in-between a lot of the other ice, but then sometimes when she has to have birth before, you know, when she has the contractions and stuff, she'll go to first available ice and have her calf, and then abandon that area as soon as the calf is strong enough to leave. The walruses have even grabbed their young to escape from predators, like that, and then take [th]em into the water… yeah, they go in under the water, probably 2 minutes, resurface; the mother will still be holding the calf.

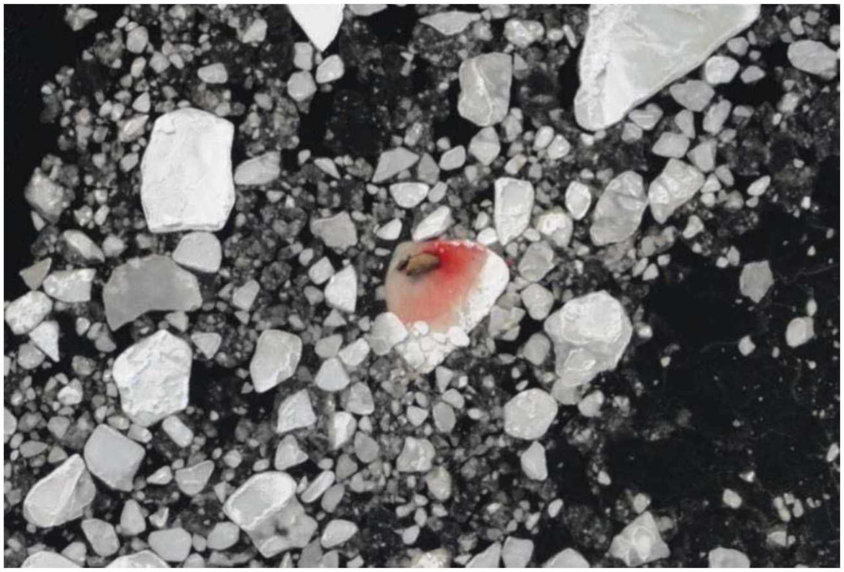

Figure 3.5 Walrus giving birth on a small, segregated floe away from the herd. Calving walruses tend to choose floe patches that offer a number of possible birthing floe platforms, but may take the first available floe, if there's limited choice.

Figure 3.6 Walrus grouping structure during calving season. Here, walrus juveniles are segregated from the females and YOY newborn walrus.

Female walruses with YOY and juveniles sometimes become spread out (Figure 3.6). After calving, while the female has rejoined the group and is caring for her newborn calf, other walruses of the group are segregated and huddle up in a different area. In this image (Figure 3.6), the importance of ridging deformation is emphasized, as walruses hide behind rubble piles. Informant A from Savoonga described walrus groups that consist of YOY may also group on a floe in a protective orientation, ready to escape from predators into the nearby water, YOY first (Figure 3.7). In this group arrangement, the YOY walruses are near the edge of the floe, with the adult bull walruses in the center of the group, behind them in a defensive orientation. This can also help to avoid a stampede of walrus, killing the YOY if the walruses become aware of the presence of a predator. Typically, this grouping tends to have 12 – 14 mature female walruses, two to three bulls, and the YOY calves. Informant A describes these conditions as a protective measure:

> Most of these bigger groups of walruses like this, if they have calves, all the calves, calving walruses would be on the edge. All on the edge of the ice, cause the mother walrus wants to get off with its calf right away and avoidance of a stampede that might happen, and like, walruses are very protective of their young. You know, they'll even attack a boat… Yeah, and most of the time when we get to a group a-walruses that have calves, would be mainly like on these small or flat ices. Okay. Up to 12, 14 females will be in the ice floe bout that big and each of these calves and female walruses will be on the edge of the ice; small ice, and then there'd be…two or three bulls right in the center of the herd… of the female walruses. These are the males that are dominant that have this herd. They're the ones that, you know, the females will even protect the two males that are right there…each herd will have, you know, an average of 12 – 14 females that have same reproduction from those two bulls, yeah, and the female will have 3 to 4, you know, calves within 3 or 4 years and each of the calves that she had will live with that group until you know, until its fully mature and leaves that herd for another herd.

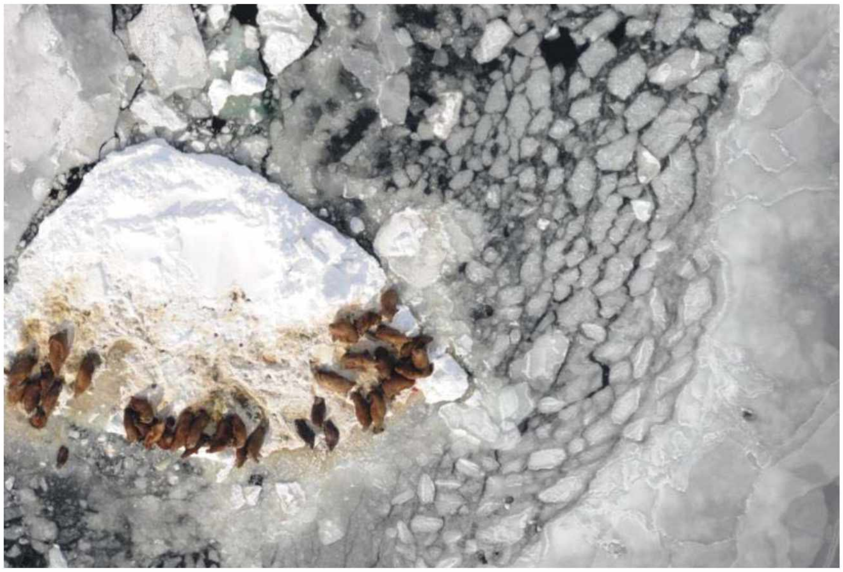

Figure 3.7 Walrus grouping structure for the protection of YOY. Walruses group in this way to protect the YOY calves from potential predator attacks.

3.6 Ice features important to walrus

Walruses use sea ice to rest between foraging bouts, birth and raise YOY, migrate north for the summer season, and to avoid predators. During the spring months, walruses must migrate to the Chukchi Sea and also avoid predators such as killer whales, polar bears, and humans. Alaskan Native subsistence hunters have observed and harvested walruses for thousands of years. This familiar knowledge of the ice and climate conditions surrounding these subsistence communities can assist in more-accurately describing walrus-ice associations.

Informant A from Savoonga and B from Gambell observed that walruses typically preferred to haul out on ice floes that displayed large ridge deformation (Figure 3.8). Near these features, or if possible between them, the walrus would select to shield itself from cold wind and predators, as Informant A from Savoonga describes:

> The smart thing about, with the mother walrus, if she was to hide, get down, a predator would come in [and] she'd go down and go in-between these little ices that have a high, high point and she'd you know, slowly try to get to her calf away from the predator, until she finds a good hiding place. Without these higher pressure ridges, these walruses they're more and more in danger all the time.

Recently, Informant A states, walruses are typically seen on flat ice since large ridging on ice near St. Lawrence Island is becoming less common. This flat ice is preferred by Informer A, though, for the ease of butchering their take.

Figure 3.8 Walruses hauled out on ridge-deformed floes. Walruses prefer floes with high ridges to protect them from the cold winds and to hide from predators. Photo taken 3 April, 1971 by G. Carleton Ray.

Informant D from Gambell observed that walrus males also utilized the shorefast ice. Female and young walruses were not seen on shorefast ice, but all walruses were seen on relatively smaller floes overall, as Informant D describes:

> Usually they're not on huge floes. We usually see them on you know, smaller floes but you know, in the past I've you know gone around they do kinda get on these. The shore ice. And usually it's the males, never the females. Never seen any females haul out on shore ice, but it's usually the males…Yeah usually they do haul out and you know in smaller chunks. In the past you know, I've never really seen any walruses haul out on you know large, large chunks of ice.

Mixed herds of adult males, females and juveniles, were seen on relatively larger floes than those used by females with YOY. Informant A from Savoonga agrees with these observations:

> A lot of the younger yearlings and the 2-3 year old walruses will like staying on the smaller floes… they'll like staying on the smaller pieces, yeah, but the bulls and the older females that are more mature will stay together on the bigger

ice…the mature walruses, will like the ice that have all the points and you know like the high ridges on them, where all along the shore that ice where, when it gets windy or cold, they're hiding their calves, feeding and keeping them warm.

While the size of floes was easily distinguishable to hunters of Savoonga and Gambell, the shape of the floe was not as memorable. This may be due to the sheer complexity of floe shape combinations, describing floe angularity or roundness, which is less noticeable from a hunter's perspective.

Thin ice is also an important component of an ice area preferentially occupied by walrus. It allows animals to open up breathing holes and provides access to open water when hauled out between foraging bouts (Figure 3.9). This is especially important during the winter and early spring, when young ice growth can close up leads or areas between floes, leaving the walruses stranded.

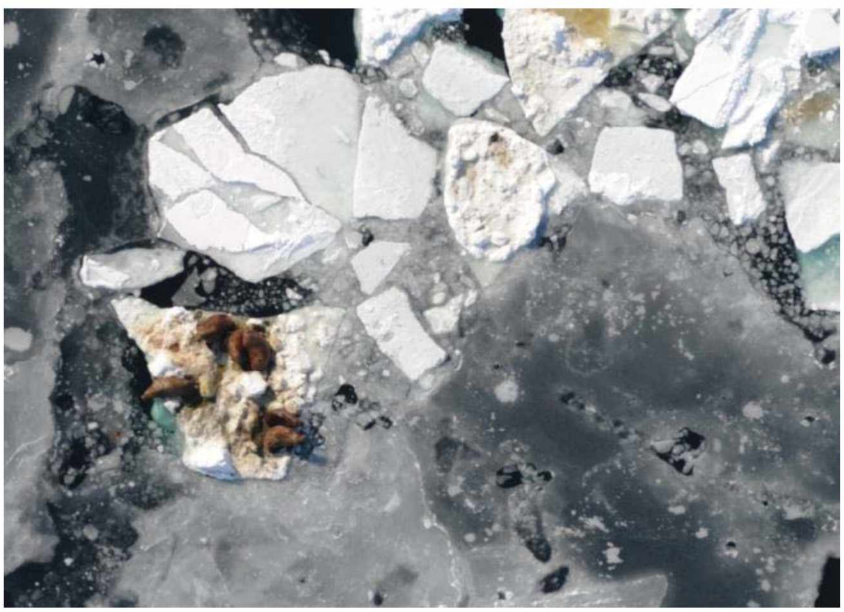

Figure 3.9 Walruses keep access to open water available. Walruses continually clear thin, young ice away from their occupied floe in order to always have access to open water to avoid predators or to forage.

Figure 3.10 Walruses occupy an ice patch that limits access by predators. Hunters state that situations like the one shown here are less safe when hunting walruses and are best left alone due to the threat of a lead closing while hunters are traversing it.

Arrangement of local spatial-scale ice areas that offer limited accessibility from the outside are observed to be occupied by walruses (Figure 3.10). This patch arrangement is especially difficult for a hunting party. In situations like these, with only one or two access points in which a hunting party can engage a group of walrus, sea-ice leads are considered unsafe, as described by Informant A from Savoonga:

> See, when we're out hunting sometimes, we see walruses in a group like this (Figure 3.10). The entrance and exit, very narrow; we try to avoid those… and it can cause, you know, hardship of trying to pull your boat out on top of the ice. Yeah, it's why we try to, you know, when we see a group of walruses that's too far inside the ice, don't mess with them. Even though they look like, all good, yeah. We got walrus and then it's like the condition of the ice, it's like that. And they're way far in there. Not worth the trip.

Signs that an ice area is highly dynamic and should be avoided can be seen in Figure 3.11 and is described in detail by Informant A:

> Yep, ice piles up pretty fast. This is caused by high winds. Okay, you see, where there's water, on the interior part of the ice? When the weather gets windy and rough, the high winds take all the smaller other ice and piles it up, all on a pile

> and the waves constantly bang on the ice. Do you see the wet part out here? This is from all from high winds. The wind does this. The weather gets real windy. The ice breaks up quicker.

Other access points are sought, but safety is the main priority. Walruses can use these tight leads for open-water access, environmental barriers from predators, and pressure ridges associated with leads to hide behind. The definition or selection of specific descriptors of ice patches need to consider walrus behavior such as that identified by informants and summarized here.

Figure 3.11 Ice areas that are highly dynamic sometimes have indicators to watch out for. Here, a lone walrus sits on a floe, but small ridges and areas on top of the ice with water near the ridges can be descriptors of an area that experiences recent or continuing convergence and brittle failure of floes.

3.7 Discussion

Ice conditions described in the spring of 2015 and of conditions in 2014 show that sea-ice is becoming thinner, arriving later, and preventing hunting opportunities of subsistence hunters, compared with observations from 2000 – 2001 discussed in Oozeva et al. (2004). During that winter and spring, ice appeared by late November, with a solid shore ice cover forming mid-to-late January (Oozeva et al. 2004), almost 2 months earlier than observed in 2015. Ice around

Gambell during the fall freeze-up is as described above in section 3.4, when ice breaks away to the open sea before forming a sturdy platform along the coast, only to return again. These conditions are described as ice being blown away and returning again a short time later (Oozeva et al. 2004). This ice, described as *akitaaghhaak*, is not safe to walk on and is not to be depended on (Oozeva et al. 2004). As described by Informants A from Savoonga and B from Gambell, the February slush ice cover reduces the number of successful subsistence hunts and opportunities to pursue prey, but also causes a "ripple effect", as described by Informant D from Gambell, for the entire community, since subsistence is providing food and materials for handicrafts, which can bring income to the communities from the selling of native works of art.

Each general category of ice-patch descriptor identified in the remote sensing research above (floe size, shape, and arrangement) (*see* Chapter 2, Table 2.1 was discussed with ice, climate, and walrus experts in Savoonga and Gambell, St. Lawrence Island during the interviews. In general, traditional knowledge shared by informants disagreed with the finding of this study that adults with YOY were in ice patches that contained larger area floes than adults and juveniles. However, since floe perimeter is smaller for those ice patches with YOY present, this may be attributed to how these variables are perceived or defined by individuals. A larger floe density was observed when YOY and adults are present in an ice patch, agreeing with previous findings. However, one important point is that the walruses with YOY or a calving female will choose the first available floe. This agrees with Jay et al. (2010), who found that walruses typically do not revisit the same floe during diving forays. However, this study did not investigate whether the walruses returned to the same general area, or ice patch. TEK experts referred to sea-ice concentrations in more general terms, but ice concentration variation was not stressed as important. Access to open water and the ability to break through thin ice, if present, as well as access to ice thick enough to haul out on and not sink, were all mentioned as important characteristics of ice that walruses would seek out.

While ice-patch descriptors and TEK did not fully agree with each other on important ice characteristics, this can partially be accounted for by differences in the associated spatial and temporal scales. Spatially, the data cover two different areas and perspectives. The ice-patch perspective looks at the ice-water system as a static feature, assuming conditions stay the same or similar over time of walrus occupation. At a larger spatial scale, such as an ice patch, this is reasonable over shorter periods of time. The perspective of the hunter is one with floes moving relative to the observer, with constant ice-ice interactions. These TEK observations and comparison with quantitatively-derived ice-patch analysis results must also take into consideration wind and weather conditions that may prevent a hunting party to travel onto the ice or ocean. Environmental factors such as low (< 30%) ice concentration, high winds, and good visibility are relevant for boating safety and hunting success (Kapsch, Eicken and Robards 2010). During days of low wind speeds and low air temperature (< -20° C), leads are more likely to freeze over, reducing the amount of open water to use during the hunt (Kapsch, Eicken and Robards 2010). Thus, observations may only relay a select set of ice properties that walruses are typically seen on, while missing other properties that may be as important to walruses.

The patch descriptors mentioned previously were found to be important to walrus occupation at the ice-patch scale (< 4 km^2), but they are not as easily distinguishable or memorable descriptors in practice to TEK experts. Most observations and TEK focused on specific floes rather than a measureable area of ice and water. The walrus' interaction with its immediate environment is evident in the previous sections of this paper. However, there were some specific ice characteristics that were not studied in the remote sensing study. Large ice ridges are one standout property of sea ice floes that was stressed by hunters, both in Gambell and Savoonga, as important to walrus occupation. This property, while challenging to measure through aerial photographs, is regularly present in the walrus-occupied imagery studied. Recently, large ice ridges have been seldom observed in the St. Lawrence Island area. As mentioned above, the ice has become brash, thin, and unreliable and shorefast ice is short-lived and unsafe. Large expanses of open water are located near Gambell throughout a large portion of the winter-spring season and ice that is rotten, sediment-laden, and too thin to use by both predator and prey has recently become commonly observed in the area for the last few years. Large ice ridges can be an indication of highly-dynamic ice areas and also potential highly-valued walrus haul-out areas. Consultation of traditional knowledge holders before an ecological study commences, even one relying on remote sensing data, should be a priority (Eicken 2010). In this study's case, important features of the sea-ice area, such as ice ridges, can be recognized and potentially result in quantification of habitat features that may have not been previously considered or observed in ecological studies.

3.8 Conclusions

When talking about walruses and climate change, the hunters and elders agree that walruses are resilient animals and that, as long as there is a food source and thick enough sea ice around, the walrus will continue to thrive. While walruses are typically found associated with specific ice types, from talking with these hunters and elders, the type of ice appears to change with the changing ice and climate characteristics. The walrus is viewed as an adaptable food source. Recently, walrus harvesting in Savoonga and Gambell have been on the decline, which has prompted an economic disaster declaration from the state of Alaska in 2013, and will be sought in 2015 by the community of Gambell (Caldwell 2015). With changing sea-ice and climate conditions in the Arctic, residents of St. Lawrence Island communities are finding it more difficult to harvest enough walrus to feed their communities than in the recent past. While harvesting has declined in recent years, the community members are faithful that the availability of walruses will continue to provide food and supplies for the communities that depend on them.

3.9 Acknowledgements

This research was supported in part by a UAF Center for Global Change Student Research Grant with funds from the Cooperative Institute for Alaska Research. This research was also supported in part by National Science Foundation award #1125040, CDI-Type I: Collaborative Research: A Computational Thinking Approach to Mapping Critical Marine Mammal Habitat Through Readily-Deployable Video Systems. Images presented in this study were collected through the 2012 NOAA Bering-Okhotsk Seal Survey (BOSS). The NOAA BOSS program collected images under the National Marine Fisheries Service (NMFS) Marine Mammal Protection Act (MMPA) Permit #15126, in order to be in close proximity to marine mammals during flights. We are very grateful to the Eskimo Walrus Commission, especially Vera Metcalf, for supporting the project through each stage of the study.

3.10 References

Caldwell, Suzanna. 2015. "Alaska Village Ponders next Steps as Walrus Harvests Decline Drastically." Alaska Dispatch, July 8. http://www.adn.com/article/20150708/alaska-village-ponders-next-steps-walrus-harvests-decline-drastically.

Eicken, Hajo. 2010. "Indigenous Knowledge and Sea Ice Science: What Can We Learn from Indigenous Ice Users?" In SIKU: Knowing Our Ice, edited by Igor Krupnik, Claudio Aporta, Shari Gearheard, Gita J. Laidler, and Lene Kielsen Holm, 357–76. Springer Netherlands. doi:10.1007/978-90-481-8587-0_15.

Fay, F.H. 1982. "Ecology and Biology of the Pacific Walrus, Odobenus Rosmarus Divergens Illiger." North American Fauna, 1–279. http://www.fwspubs.org/doi/abs/10.3996/nafa.74.0001.

Fay, Francis H., G. Carleton Ray, and A.A. Kibal'chich. 1984. "Time and Location of Mating and Associated Behavior of the Pacific Walrus, Odobenus Rosmarus Divergens Illiger." Vol. 1.

Huntington, Henry P. 2000. "Using Traditional Ecological Knowledge in Science: Methods and Applications." Ecological Applications 10 (5). Ecological Society of America: 1270–74. doi:10.2307/2641282.

Jay, Chadwick V., Mark S. Udevitz, Ron Kwok, Anthony S. Fischbach, and David C. Douglas. 2010. "Divergent Movements of Walrus and Sea Ice in the Northern Bering Sea." Marine Ecology Progress Series 407: 293–302. doi:10.3354/meps08575.

Kapsch, Marie-Luise, Hajo Eicken, and Martin Robards. 2010. "Sea Ice Distribution and Ice Use by Indigenous Walrus Hunters on St. Lawrence Island, Alaska." In SIKU: Knowing Our Ice, edited by Igor Krupnik, Claudio Aporta, Shari Gearheard, Gita J. Laidler, and Lene Kielsen Holm, 115–44. Springer Netherlands. doi:10.1007/978-90-481-8587-0_5.

Krupnik, Igor, Leonard Apangalook Sr., and Paul Apangalook. 2010. "'It's Cold, but Not Cold Enough': Observing Ice and Climate Change in Gambell, Alaska, in IPY 2007 – 2008 and beyond." In SIKU: Knowing Our Ice, edited by Igor Krupnik, Claudio Aporta, Shari Gearheard, Gita J. Laidler, and Lene Kielsen Holm, 81–114. Springer Netherlands.

Krupnik, Igor, and G. Carleton Ray. 2007. "Pacific Walruses, Indigenous Hunters, and Climate Change: Bridging Scientific and Indigenous Knowledge." Deep Sea Research Part II: Topical Studies in Oceanography 54 (23–26): 2946–57. doi:http://dx.doi.org/10.1016/j.dsr2.2007.08.011.

Oozeva, Conrad, Chester Noongwook, George Noongwook, Christina Alowa, and Igor Krupnik. 2004. Watching Ice and Weather Our way/Sikumengllu Eslamengllu Esghapalleghput. Edited by Igor Krupnik, Henry Huntington, Christopher Koonooka, and George Noongwook. Washington, D.C.: Arctic Studies Center, Smithsonian Institution.

Ray, G. Carleton, Jerry McCormick-Ray, Peter Berg, and Howard E. Epstein. 2006. "Pacific Walrus: Benthic Bioturbator of Beringia." Journal of Experimental Marine Biology and Ecology 330 (1): 403–19. doi:http://dx.doi.org/10.1016/j.jembe.2005.12.043.

Ray, G. Carleton, James E. Overland, and Gary L. Hufford. 2010. "Seascape as an Organizing Principle for Evaluating Walrus and Seal Sea-Ice Habitat in Beringia." Geophysical Research Letters 37 (20): n/a – n/a. doi:10.1029/2010GL044452.

Robards, Martin D., Alexander S. Kitaysky, and John J. Burns. 2013. "Physical and Sociocultural Factors Affecting Walrus Subsistence at Three Villages in the Northern Bering Sea: 1952–2004." Polar Geography 36 (1-2). Taylor & Francis: 65–85. doi:10.1080/1088937X.2013.765519.

U.S. Census Bureau. 2010a. "Profile of General Population and Housing Statistics: Gambell City, Alaska." http://factfinder.census.gov.

———. 2010b. "Profile of General Population and Housing Statistics: Savoonga City, Alaska." http://factfinder.census.gov.

Vermote, E., R. Wolfe, NASA GSFC, and MODAPS SIPS-NASA. 2015. "MYD09GQ MODIS and the Aqua Surface Reflectance Daily L2G Global 250m SIN Grid V006." NASA EODIS LP DAAC. doi:http://doi.org/10.5067/MODIS/MYD09GQ.006.

Appendix 3.A

Institutional Review Board Approval Letter for IRB# 662539-2

UNIVERSITY OF ALASKA FAIRBANKS

(907) 474-7800
(907) 474-5444 fax
uaf-irb@alaska.edu
www.uaf.edu/irb

Institutional Review Board

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

January 29, 2015

To:	Hajo Eicken Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[662539-2] Sea ice conditions and walrus migration near St. Lawrence Island: Integrating local knowledge for assessing change and interpreting satellite data

Thank you for submitting the Amendment/Modification referenced below. The submission was handled by Administrative Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Sea ice conditions and walrus migration near St. Lawrence Island: Integrating local knowledge for assessing change and interpreting satellite data
Received:	January 28, 2015
Expedited Category:	7
Action:	APPROVED
Effective Date:	January 29, 2015
Expiration Date:	January 29, 2016

Required Information:

Administratively approved per Expedited instructions on previous package.

This action is included on the February 4, 2015 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

Appendix 3.B

List of Semi-directed Questions

Sea ice conditions during this fall freeze-up and spring melt around St. Lawrence Island

1. How do you feel about the ice this year? How would you compare this year's freeze-up to other freeze-up conditions you have experienced? Based on what you've seen of the ice so far this year, how do you think the ice season will be near your village?

2. How would you describe the landfast ice during winter hunting seasons, in general? Is ice typically ridged or smooth?

3. How would you describe the drifting ice this hunting season?

Walrus behaviors, abundance, and migration and associated ocean, weather, and ice conditions: Past and present time periods and use of remote sensing in safety

4. What are some walrus behaviors you've seen in recent years in how they use the ice?

5. Do you have a memory of another year that had the same type of walrus, ice, ocean, or wind conditions as you did this year?

6. Have you seen ways that weather from one season can tell you how the next season will be?

7. What types of sea ice do you typically see in areas around your village when you hunt for walrus?

8. Can you show me where you find these different ice types during fall freeze-up and spring melt?

9. How do you decide whether the weather conditions are safe enough to go hunting for walrus? How do landfast ice and drifting ice conditions determine how hunting will be for walrus?

10. How can you tell that walruses are nearby from the wind, ocean and ice?

11. Have you observed any changes in walrus female and young or male numbers during migration in recent time?

Historical knowledge, customs, beliefs, and harvests during walrus hunting periods

12. What have you heard from the elders in your village about finding walruses in past times that you have not seen yourself?

13. What are ways to be safe on the ice that you learned from elders before you began to hunt? Have you found new ways to be safe on the sea ice during your hunting experiences that elders did not teach you?

14. How do you teach the new generation of subsistence hunters about safety when hunting walruses and traveling on ice in recent years and how has this compared to the past?
15. How have the ice, weather, and walrus conditions affected your village's ability to have successful harvests over the past few years?

4 Conclusion

Pacific walruses use sea ice for various life-cycle events, some events requiring specific sea-ice types and arrangements. These events can be associated with specific spatial scales of analysis, defining relevant processes and characteristics of the ice pack. At two spatial scales, the ice-patch scale (< $4km^2$) and the seascape scale (100 km^2), walruses show associated ice descriptor or seascape preferences, each outlining ice characteristics important for biological needs and sustainability. Quantitatively studying these ice associations for walruses brings new techniques that encompass not only geophysical, but ecological considerations in defining habitat. Sea-ice associations to walrus natural history can be described at the patch scale defining size, shape, and patch-arrangement descriptors, while seascapes have amply described this at the larger mesoscale. Fragmented pack ice is the preferred seascape, using a two-class SAR algorithm that defines habitat during the spring melt season in the Bering Sea. At the patch scale, floe density, convexity, and local-scale concentrations of sea ice and open water represent features of the ice patch that walruses may prefer. Beyond these features, another important perspective is that provided by traditional ecological knowledge from subsistence hunters that live in this environment. Insight into important ice features, such as ice ridges, are important to walrus, but their disappearance with the changing sea-ice pack forces both hunter and walrus to adapt to these changes.

Data to accomplish these goals should exhibit a wide range of resolutions, scales, perspectives, and coverages, to obtain a complete picture of species-environment associations. Sea ice currently is in a transition from a perennial to potentially a seasonal seascape and, as such, examination of ice characteristics at finer scales than that gained from passive microwave data will provide a more complete picture of how the ice is changing beyond concentration and extent. Walrus surveys that study winter presence and ice use, from November to March should also be conducted to assess those ice characteristics important during mating and copulation events, a critical time in the walrus' life cycle. Further enhancement of the geophysical and remote sensing techniques used is needed to completely describe and define habitat. Techniques to define and quantify surface features such as ice ridging, snow cover, distance between floes, as well as ice thickness quantification and techniques to reliably complete edge floe shape and size in order to obtain a complete view of ice characteristics would be useful in what descriptors of the ice walruses may depend on. Inclusion of environmental variables, such as wind speed and direction, ocean current motion, ice velocity and direction, surface air temperature, and walrus food-source areas would relate the entire environmental system to walrus observations. These variables may be related to a walrus' choice of ice patch, seascape, and other scales of ice interaction.

The seascape ecology techniques devised here can be applied to various other pagophilic marine mammals, but more abstractly, to any marine animal that depends on characteristics of the marine landscape for their natural history. Extending landscape ecology techniques and paradigms to the marine realm provides not only challenges examining relevant properties that can be directly applied, but also describing environmental characteristics in a three-dimensional space. Habitat partitioning, such as that studied by Braham et al. (1984), could include not only pinniped use of sea ice, but cetaceans, as well as pinniped and cetacean predators, in order to develop habitat mapping inclusive of the surrounding species community. One such example is the bearded seal and the Pacific walrus, which tend to occupy the central winter ice pack, using floes to haul out on (Ray, Overland and Hufford 2010). Delineation of these species-range interactions and spatial distinction could provide further insight into walrus distribution and how that may change in relation to other non-threatening marine mammals. These resulting analyses can provide new ways to define marine protected areas for endangered or threatened species, better understand optimal fisheries distribution, and determine quantitative definitions of important species' traits that contribute to sustainability and conservation. Management and conservation efforts can utilize these habitat maps to describe adaptation and critical boundaries of habitat loss to help describe fitness of the species and investigate effects of outside anthropogenic stresses. Stakeholders, such as energy companies, shipping and tourism businesses, federal marine species protection managers, and subsistence hunters will benefit from an increased definition of important habitat designations. Further work on expanding these walrus-ice associations will help to better understand why sea ice is such an important part of habitat, but also the specific importance of sea ice to megafauna in a changing Arctic climate.

4.1 References

Braham, Howard W, J.J. Burns, G.A. Fedoseev, and B.D. Krogman. 1984. "Habitat Partitioning by Ice-Associated Pinnipeds: Distribution and Density of Seals and Walruses in the Bering Sea, April 1976." In Soviet-American Cooperative Research on Marine Mammals . Volume 1- Pinnipeds, edited by Francis H. Fay and Gennadii A. Fedoseev, 25–47. National Oceanographic and Atmospheric Administration.

Ray, G. Carleton, James E. Overland, and Gary L. Hufford. 2010. "Seascape as an Organizing Principle for Evaluating Walrus and Seal Sea-Ice Habitat in Beringia." Geophysical Research Letters 37 (20): n/a – n/a. doi:10.1029/2010GL044452.